

# DEVELOPMENT OF A PHOTO-INJECTOR LASER SYSTEM FOR KEK ERL TEST ACCELERATOR

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## Abstract

We have been developing a laser system for a photo-cathode gun of an ERL test accelerator which is under construction at KEK. A high average power laser amplifier based on an Yb-doped photonic-crystal fiber has been developed. 70 W output power of 1.3 GHz repetition rate at 1064 nm wavelength has been demonstrated. This will be converted to the second harmonics of 532 nm, and then will be delivered to the cathode.

## INTRODUCTION

A synchrotron radiation source based on Energy Recovery Linac scheme has been expected to be a next generation light source which generates high average brightness and short pulse X-rays. KEK has been constructing a test ERL accelerator (cERL [1]) to develop key components and to have operation experiences before proposing a GeV-class light source machine. In order to realize a low emittance and a high current beam, a photo-cathode DC gun has been chosen as the electron source. It is designed to provide an average current of more than 10 mA, normalized emittance of lower than  $1 \mu\text{m}$ , pulse duration of 30 ps, at a quasi-continuous mode of 1.3 GHz repetition rate. Since 2011, KEK has been developing a laser system to excite the photo-cathode. This presentation reports the development work of the high average power fiber laser amplifier system.

## OVERVIEW OF THE LASER SYSTEM

Assuming GaAs-based photo-cathode and its quantum efficiency to be 1%, 1.5 W of power at a wavelength of  $\sim 500 \text{ nm}$  is required on the cathode. Fig.1 shows the scheme of the laser system. It consists of an oscillator, an amplifier system and a wavelength conversion system. A pulse shaping system in both spatial and temporal profile, a pulse train forming system to support various operational modes, intensity and pointing stabilization system, and interlock system are to be implemented.

An Nd:YVO<sub>4</sub> passive mode-lock laser oscillator (GE-100, TimeBandwidth product) is chosen to start with a well established one in accelerator labs.

An Yb-doped photonic-crystal fiber (PCF) based amplifier features high gain and high efficiency amplification in a fundamental transverse mode. Since this system requires handling a high average power with a relatively low peak intensity, a fiber based scheme seems to be suitable. A multi-stage system is designed for efficiently amplifying the signal wavelength of 1064 nm which is off the gain peak

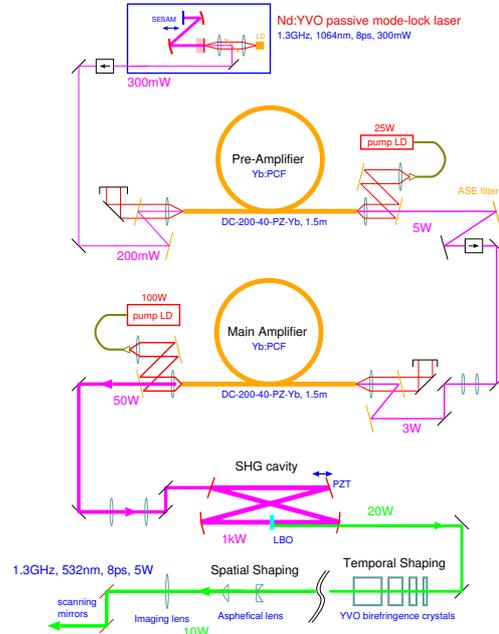


Figure 1: Scheme of the laser system.

of Yb.  $\sim 50 \text{ W}$  power of IR is expected at the output of the amplifier. This should be further upgraded to multi-100W with additional stages in the future upgrade of cERL.

In order to improve the efficiency of second harmonics generation, a novel system with an enhancement cavity has been proposed.

## DEVELOPMENT OF FIBER AMPLIFIER

### Characterization of the fiber amplifier

Yb-doped PCF (DC-200-40-PZ-Yb, NKT photonics), which has a core diameter of  $40 \mu\text{m}$  and an inner cladding diameter of  $200 \mu\text{m}$  is used. It is pumped by a fiber coupled laser diode of 976 nm wavelength. We have started with a test measurement for characterizing the performance of the fiber.

A fiber amplifier pumped at the end can be modeled by a 4-levels laser system extended with a variation of pump ( $P$ ) and signal ( $I$ ) power in the longitudinal direction ( $z$ ) as the following differential equations.

$$\frac{dP(z)}{dz} = -A \frac{1 + I(z)/I_s}{1 + P(z)/P_s + I(z)/I_s} P(z) \quad (1)$$

$$\frac{dI(z)}{dz} = G \frac{P(z)/P_s}{1 + P(z)/P_s + I(z)/I_s} I(z) \quad (2)$$

The system at the given wavelength can be expressed with 4 parameters,  $A$ ,  $G$ ,  $P_s$ ,  $I_s$ . Based on the parameters deter-

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mined from a set of low power tests, we have optimized the length of the fiber and have set the requirements of pump power and input signal power.

At a high gain operation, input signal power has to be high enough and it should not contain a noise at the wavelength of Yb's gain peak, which is around 1030 nm. In order to reach 50 W output power,  $\sim 1$  W of initial power is needed.

### Setup

Detail setup of the amplifier system is shown in Fig.2. It consists of a pre-amplifier stage which is pumped by a 25 W laser diode and a main-amplifier stage which is pumped by a 100 W laser diode. The design of the two stages are basically the same. A wavelength filter to remove spontaneous emission component of 1030 nm (ASE) is inserted between the stages.

PCF of 1.5 m terminated with high power connectors are used. The ends are supported by water-cooled mounts. The pump lasers are delivered with multi-mode fibers of 200  $\mu\text{m}$  core. It is imaged on the fiber ends by a demagnification optics.

Since the PCF is a single mode fiber, it only accepts the fundamental transverse propagation mode. Transverse mode of the injection signal has to be carefully tuned to coincide with the fiber mode. A special system utilizing a reference optical cavity has been developed to optimize the signal matching. A 4-mirror optical cavity which has a round trip length that corresponds to 4th sub-harmonics of 1.3 GHz defines a reference transverse mode. By observing higher order modes excitation of the reference cavity, a laser beam incident to the cavity can be tuned to the reference mode in a systematic way with a mirror pair which controls optical axis and a lens pair which controls beam waist. Tuning between the reference cavity to the fiber can be done by switching to the alignment laser path which supplies a counter propagation light through the fiber mode to the reference cavity. Then, after tuning the beam from upstream to the cavity, a perfectly mode matched optics from upstream to the fiber can be established.

### Results

The pre-amplifier was set to output 2.8 W and input power of the main-amplifier was 2.6 W. Fig.3 shows output power of the amplifier system as a function of input pump power of the main-amplifier. It reached 70 W at 110 W power of the pumping laser.

Fig.4 shows the spectrum of the amplified output. Thanks to the ASE filter, ASE noise around 1030 nm wavelength was suppressed to lower than -50 dB of the signal level. Although there noticed to be a deformation of the spectrum shape depending on the output power, no significant spectrum width broadening are seen.

Fig.5 shows the pulse width measurement using an auto-correlator. Assuming gaussian profile, RMS pulse width was estimated to be 5 ps. No significant pulse lengthening are seen.

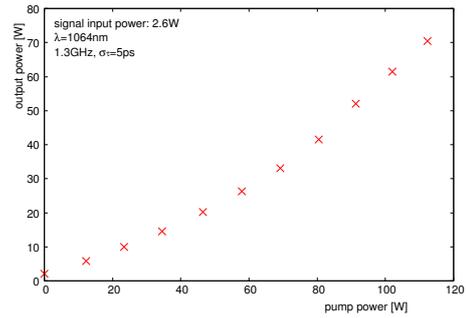


Figure 3: Output power of the amplifier system.

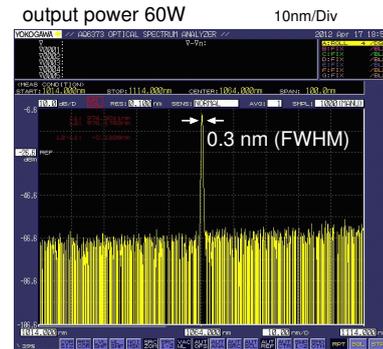


Figure 4: Optical spectrum of the amplified output.

Overall, we have confirmed that the multi-stage amplifier works as expected. A test on long term stability has been carried out at an output power of 36 W. Fig.6 shows the result. It has shown peak-to-peak power variation within  $\pm 0.5\%$  in more than two hours without any feedback system after it reached to a steady state. The test was only limited by the experimental time.

### TEST OF WAVELENGTH CONVERSION

IR output of the amplifier is then injected into a non-linear birefringent crystal for the second harmonics generation. Two schemes are under development.

The first one is a single path system. Assuming conversion efficiency to be  $\sim 1\%/W$ , 4 W of second harmonics power is expected at 20 W of IR from a calculation of an ideal case. It seems to be enough for the first commission-

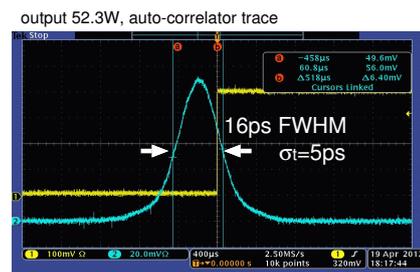


Figure 5: Pulse width measurement of the amplified output.

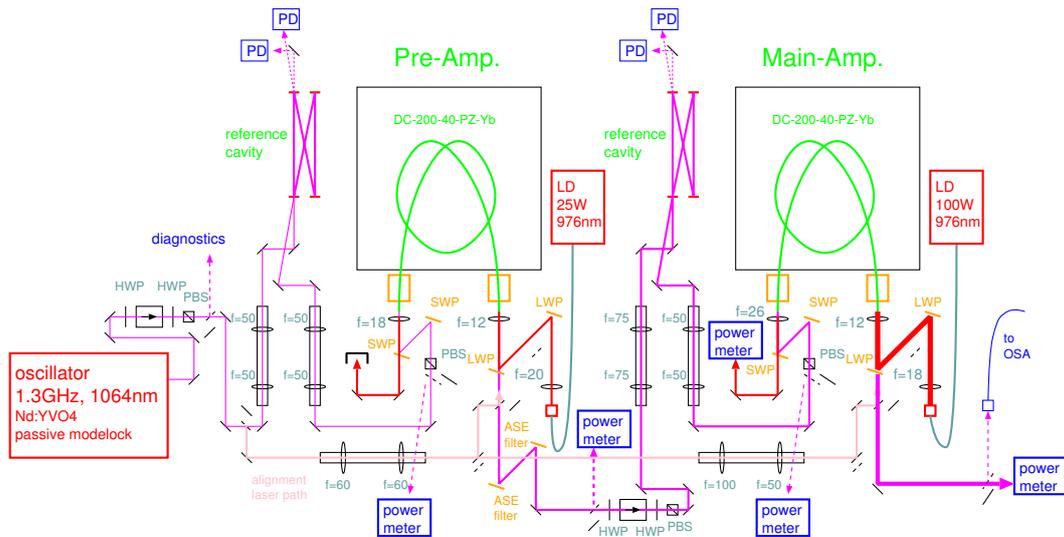


Figure 2: Setup of the amplifier system.

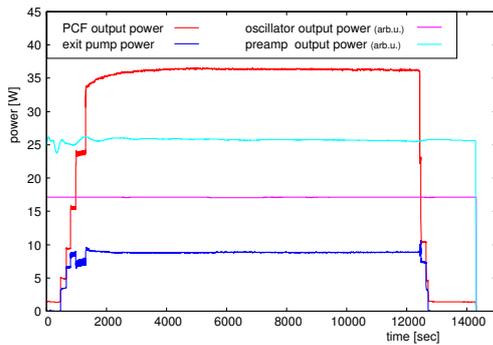


Figure 6: Long term stability test.

second harmonics is expected at 23 W IR.

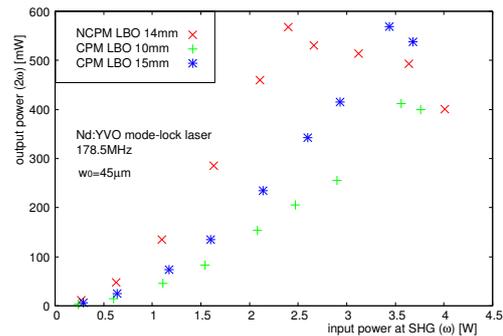


Figure 7: Second harmonics generation.

ing of cERL. If higher IR power improves the efficiency as it is expected from the non-linear nature, it is expected to realize a good enough power when upgrading the amplifier stage in the future. In this approach, handling of a high average power in the crystal, quality of amplified laser pulse to keep the ideal conversion efficiency are to be established.

The second one is a cavity scheme. By putting the crystal inside of an enhancement cavity where the effective IR intensity can be much higher, conversion efficiency can be improved even at a relatively low amplifier output. The enhancement cavity should be designed to be a heavy loaded condition that the wavelength conversion dominates the total loss. It is also a feature that the beam profile of IR at the crystal and that of second harmonics is well defined due to the cavity nature.

In order to test conversion efficiency for a high intensity pulse, a test has been done with a single stage amplified pulse of lower repetition rate. LBO crystals of critical and non-critical phase matching are tested at a single path setup. The results are shown in Fig.7. 0.5 W of second harmonics power was generated from 3 W of IR power at 178.5 MHz. By scaling this result to 1.3 GHz, 3.6 W of

## SUMMARY AND FUTURE WORK

A photo-cathode laser system for KEK-cERL has been designed. A two-stage Yb-PCF amplifier system that can amplify 1064 nm wavelength up to 70 W average power has been developed. Tests of wavelength conversion system which follows the amplifier system has started. Next study is to demonstrate the target power of second harmonics. Beam delivery system to the cathode and setting up of various functions that are necessary for an accelerator system has to be prepared.

## ACKNOWLEDGMENT

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## REFERENCES

- [1] N.Nakamura, "Review of ERL projects at KEK and around the world", TUXB02, these proceedings.