

# 25 Hz SUB-MJ YTTERBIUM LASER SOURCE OF RF GUN FOR SUPERKEKB

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## Abstract

The electron beams with a charge of more than 5 nC and a normalized emittance of less than 10  $\mu\text{m}$  are expected to be generated in the photocathode RF gun at the injector linac of SuperKEKB. An ytterbium (Yb)-doped fiber and Yb:YAG thin-disk hybrid laser system with a center wavelength of 259 nm and a pulse width of 20 ps is developed to obtain high peak energy pulses. As the result, more than 3 nC and 1 nC electron were generated in repetition of 25 Hz with single-bunch and double-bunch respectively.

## INTRODUCTION

For injector linac of SuperKEKB project, more than 5 nC electron beams with double-bunch is expected to be generated in the photocathode RF gun. To high-current, low-emittance beams generation, the laser source with 1 mJ pulse energy, center wavelength of 259 nm and a pulse width of 20 ps are needed [1]. Especially, the broadband wavelength is required for the pulse shaping control. Therefore, a Ytterbium (Yb)-doped hybrid laser system, include an Yb-doped fiber oscillator, Yb-doped fiber amplifiers and thin-disk Yb:YAG amplifiers is developed.

For the repetition rate of electron beam, the optional of 2 Hz, 5 Hz, 25 Hz and 50 Hz with single or double bunch were requested. Although, more than 5 nC electron with single-bunch has been generated in the 2 Hz and 5 Hz [2], when the repetition rate increases to 25 Hz, the condition of the laser amplifier system such as the thermal lens effect is changed seriously. To correspond to 25 Hz repetition rate, the laser was reformed.

MHz, synchronized with 2856 MHz trigger from accelerator. After an Yb fiber pre amplifier, the pulse was chirped to  $\sim 20$  ps by a transmission grating stretcher with a spectral mask. An Yb-doped large-mode-area polarizing double-clad photonic crystal fiber was employed to the first amplification stage. Then, the pulse repetition rate of 25 Hz, double bunch was separated with two Electro-optic (EO) modulators. To increase the pulse energy, another Yb-doped LMA PCF was used. So the pulse was amplified to  $\mu\text{J}$ -level, which was strong enough to be amplified by Yb:YAG thin-disk stage. To obtain the mJ-class pulse energy, several multi-pass amplifier stages were employed. Deep UV pulses for the photocathode are generated by using two frequency-doubling stages. High pulse energy and good stability were obtained. Finally, the pulses were injected into RF gun.

## Backup of Yb Fiber Oscillator

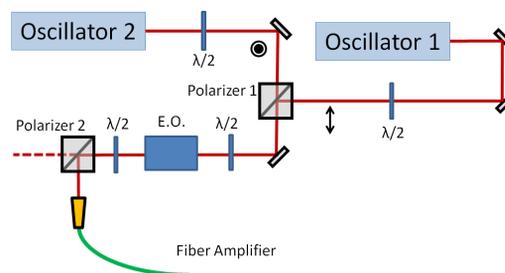


Figure 2: Selection of Oscillator.

The seed pulse was generated by a passive mode-locked oscillator with the pulse energy of 0.2 nJ at the repetition rate of 51.9 MHz (10.38\*5 MHz). The spectral bandwidth is  $\sim 50$  nm, from 1025 to 1070 nm. A piezoelectric transducer (PZT) is used to control the cavity length to lock the repetition rate with the 2856 MHz trigger from accelerator by a synchronization system. The mode-locked operation was stable for several months with good pulse quality and stability.

Because the oscillator is the most important part of all system, another backup oscillator was employed. As the fig.2, the two oscillators are set with cross polarizations that combine by polarizer 1. Then the EO modulator is used to change the polarization of the beams between the polarizer 1 and polarizer 2. The reflect beam of the seed pulses at polarizer 2 was chosen by the EO voltage control.

## Upgrade of Yb Fiber Amplifier stages

In the fiber amplifier stages, the improvement is focus on the increase of the pulse quality. Two types amplifier was set up. For low power amplification, Yb fiber with the core diameter 4  $\mu\text{m}$  same as the oscillator was used.

## LASER SYSTEM OF 25 HZ

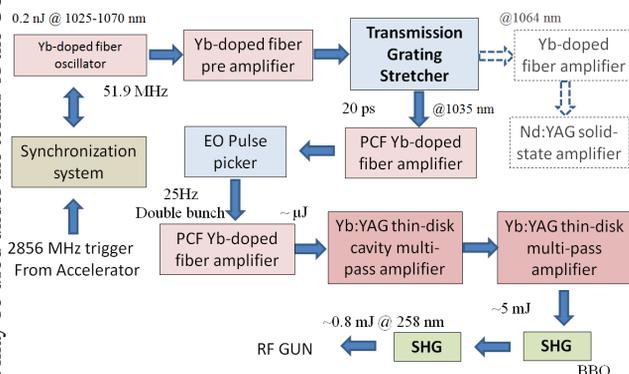


Figure 1: Layout of Laser system.

A schematic diagram of the laser setup is shown in Fig.1. The seed pulse with the pulse energy of 0.2 ns and spectrum of 1025-1070 nm was generated by an Yb-doped fiber ring oscillator. The pulse repetition is 51.9

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Laser diode (LD) pump was coupled with the wavelength-division multiplexing (WDM) coupler, which compact the construction. For high power amplification, large-mode-area (LMA) polarizing double-clad photonic crystal fiber (PCF) with a core diameter of 40  $\mu\text{m}$  was used. The signal and pump pulse focus into Yb fiber by lens in different direction. And dichroic mirrors were used to separate signal and pump beams. The isolators were set between the each amplifier to avoid the pump go back to signal.

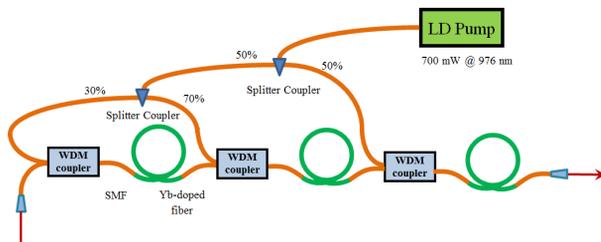


Figure 3: Yb-doped fiber pre amplifier.

In the low power amplification, the weak seed pulse makes the amplified spontaneous emission (ASE) easy to be generated. The ASE noise will be amplified during each amplifier, which reduces the conversion efficiency of the second harmonic generation (SHG) stage. For amplify the seed pulse effectively, one LD was separated to 3 parts with the output power of 15%, 35%, 50%, respectively. Seed pulse was amplified step by step (As fig3). All the 3 amplifiers were coupled each other with no free space, which reduced energy loss.

The pair of transmission gratings with a groove density of 1740 grooves/mm is used to stretch the pulse to several tens ps with gratings distance of 1.5 m. For matching the gain area of Yb:YAG disk and Yb-doped fiber, a spatial slit was performed for spectral shaping between the grating pair and reflector, where the spectrum is spatially separated with a parallel beam. The spectrum of the signal was reformed to near rectangle shape with the bandwidth of  $\sim 4$  nm at center wavelength of 1033 nm. And a telescope lens was employed to reduce the beam size of the signal before the stretcher, which sharp the side of pulse shaping.

The output of stretcher is seeded into the fiber amplifier by a PCF fiber of 1.2 m, cladding backwardly pumped by a 70 W fiber-coupled laser diode emitting at 976 nm. The output power of LD was controlled in low level to inhibit the ASE noise.

Last time, the signal pulses of 51.9 MHz repetition rate were reduced to 10.38 MHz firstly by an additional EO fiber pulse picker. Because the energy loss of the fiber EO modulator is more than 90%, the amplify efficiency declined seriously with ASE noise occur. Therefore, a pulse selector consist of two EO modulator was employed to reduce the pulse repetition rate to 25 Hz with double bunch of the distance of 100 ns.

After pulse picker, the signal of 25 Hz was amplifier by another PCF Yb-doped fiber amplifier. In this stage, the

pulse was amplified to several  $\mu\text{J}$  pumped with light at a wavelength of 940 nm.

### Redesign the Thin-disk Amplifier

When the pump repetition rate increases to 25 Hz, the condition of the laser amplifier system is changed seriously in the thin-disk amplifier stages. Firstly, the thermal lens effect is occurred when the signals pass through the Yb:YAG crystal, which can be compensated by lens and telescope system. Secondly, the cooling requirement of the crystal is exceeding increased because the higher repetition rate of the pump pulse. The temperature change of the thin-disk crystal let the noise and background signal increased obviously, which affect the quality and amplify efficiency of the laser source.

The disk thickness was reduced to 0.5 mm to increase the heat remove from the crystal and avoid the thermal lens effect. Thermal conductivity was improved by a new soldering component, with the Au-Sn layers on top surface (Au-80% and Sn-20%) [3].

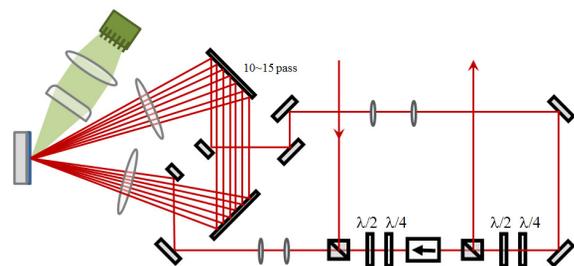


Figure 4: Thin-disk multi-pass amplifier with cavity.

For 2 Hz and 5 Hz repetition rate amplification, the regenerative thin-disk amplifier can provide effective amplification after fiber amplifier. But for 25 Hz double bunch amplification, the output energy was unstable due to the lower gain condition. The structure of the regenerative cavity is too complex to compensate thermal lens, especially the ghost pulse was difficult to reduce from first bunch due to the limited extinction ratio of the pockels cell. Therefore, a multi-pass amplifier inset into a cavity was designed to replace the regenerative amplifier.

As the fig 4, the inject signal beam with the vertical polarization was reflected by polarizer 1, and amplified 10-15 times pass through the Yb:YAG thin-disk crystal. The polarization of the amplified pulse was turn to horizontal by the wave plate, which cause the amplified pulse pass through the two polarizers and amplified again. After the two loops, the pulse went out the cavity with vertical polarization by the reflection of polarizer 2. A 2.4 kW laser diode, is employed as the pump source, with oblique injection into the Yb:YAG thin-disk crystal with a spherical mirror and a plano-convex cylindrical lens. Although more than 30 pass amplification was occurred as the regenerative amplifier, the stability and quality was increased, because no pockles cell used in the cavity.

After the cavity amplification, the simply multi-pass amplifiers were used for higher amplification. The structure of the multi-pass amplifier is shown in Fig5. The max of 6 pass amplification can be performed in a

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multi-pass amplifier. For compensate thermal lens effect, double lens was used in front of the thin-disk crystal.

The pump source was increased to 9.6 kW, with 4 laser diode setting around the Yb:YAG crystal. After the 4 multi-pass stages amplification, more than 5 mJ output pulse energy was obtained.

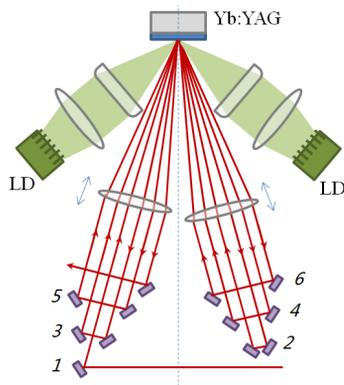


Figure 5: Thin-disk multi-pass amplifier.

Two piece of 5 mm thickness beta barium borate (BBO) crystal are used to generate ultraviolet (UV) pulses by using two frequency-doubling stages at a center wavelength of 259 nm. Because of the damage threshold limitation of the thin-disk crystal and optical mirrors, the laser pulses cannot be amplified more than 5 mJ reliably. Although the energy of fundamental beam is lower than before, the ASE pulses and background noise were inhibited. The SHG conversion efficiency of the two stages was up to 60% and 30% respectively. And the final UV pulse energy of 0.8 mJ was obtained in 25 Hz.

The distance of laser beam transmits from the laser room to the RF gun is about 15 m by several reflect mirrors. For UV pulses with center wavelength of 259 nm, the transmitting energy loss was up to 50%. Therefore, the last SHG stage was set up near the RF gun. The energy loss of the visible beam with center wavelength of 517 nm was reduced to 5%.

### Laser Injection at RF Gun



Figure 6: Charge history of RF-Gun.

The UV laser pulses are injected into the cathode in RF gun with the angle of 60°. As a result of RF gun beam measurement, more than 3.0 nC beam generation from the gun was achieved in 25 Hz, single bunch (Fig.6). The

RF-Gun cavity, cathode and experimental results will be shown in the ref [4].

### UPGRADE OF LASER SYSTEM TO 50 HZ

When the pump source repetition rate increases from 25 Hz, the heat in the Yb:YAG crystal cannot be dissipated effectively, which cause the thermal increase. Although the crystal thickness and soldering components was improved, the thermal conductivity is insufficient with 50 Hz pump condition. The amplify efficiency and beam quality decline seriously.

In contrast, Nd:YAG crystal are also pumped using a laser diodes, that offers less thermal lensing, more uniform gain than Yb:YAG. Although the pulse shaping of Nd:YAG is difficult to be adjusted because of the narrow spectrum gain, the Nd:YAG is an appropriate candidate for 50 Hz double bunch amplification. Therefore, the Nd:YAG simplify and stabilize laser system without pulse shaping will be tested in next step.

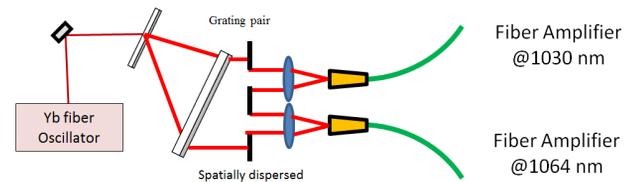


Figure 7: Spectrum separation by grating pair.

The Emission wavelength of Nd:YAG is around 1064 nm with the bandwidth of ~0.5 ns, which contained in the spectrum of Yb-doped fiber oscillator. Therefore, the Yb-doped oscillator and Yb-doped fiber amplifier also can be used with Nd:YAG amplification. As the Fig.7, the 1064 nm part of the signal pulse was separated by gratings at the stretcher stage. A additional Yb-doped fiber amplifier and Nd:YAG amplifier will be employed (Fig.1).

### CONCLUSION

For SuperKEKB project, an Yb-doped hybrid laser source is developed. The laser system contains with a Yb-doped fiber-based oscillator, large mode-area Yb-doped fiber amplifier, thin-disk Yb:YAG multi-pass amplifier systems and two SHG stages. Some improvement were performed to reduce the background noise and increase the quality of the pulses, which cause the SHG conversion efficiency is up to 60% and 30% with  $2\omega$  and  $4\omega$  respectively. More than 3 nC electron beam is obtained with 25 Hz single-bunch.

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