# TECHNICAL DEVELOPMENTS FOR INJECTING EXTERNAL LASER TO A STORAGE RING FEL IN CW AND Q-SWITCHED OPERATION

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*Abstract*

For controlling the dynamics of an oscillator-type storage ring FEL, we propose to inject the FEL oscillator with an external laser. Another purpose of the injection is generation of long-sustain and intense coherent synchrotron radiation with combining Q-switched and injected FEL. We succeeded both of them. This paper is devoted for reporting technical developments for injecting external laser to a storage ring FEL in CW and Q-switched operation.

## INTRODUCTION

The dynamics of an oscillator type storage ring FEL (SR-FEL) is strongly affected by noise of spontaneous radiation. It was reported that the dynamics of an oscillator-type storage ring FEL can be controlled by injecting very small portion of FEL output with optimal detuning condition and injection timing [1]. If small part of external seed laser can be injected to SR-FEL optical cavity with optimum timing and detuning condition, FEL emission should start from the seed laser and might be controlled by the seed laser.

Moreover, it was reported that intense and long-sustain Coherent Synchrotron Radiations (CSR) and coherent harmonic generation occur during growing stage of Q-switched SR-FEL [2,3]. There is a possibility of enhancing the intensity of the CSR driven by Q-switched SR-FEL, when short pulse external laser is injected.

We made two technical developments for enabling external laser injection to SR-FEL in CW and Q-switched operation; one is optical system, and the other is RF system. Owing to those technical developments, we succeeded in injecting external laser to SR-FEL both in CW and Q-switched operation. And the FEL lasing was mastered by external laser [4] and intensity of CSR driven by Q-switched SR-FEL was much increased [5]. This paper is devoted for reporting the technical developments.

## UVSOR-II FEL

Main parameters of UVSOR-II FEL are shown in Table 1. Usually the FEL is operated at two-bunch mode with equal bunch spacing. However, in Q-switched FEL for generating intense CSR, the FEL is operated at single bunch mode. Then the bunch repetition rate is around 5.63 MHz. Q-switching of FEL require about 1 kHz frequency jump of RF of storage ring. And the maximum repetition rate of Q-switching without power degradation is 40 Hz.

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Table 1: Main Parameters of UVSOR-II FEL

| | |
|---|---|
| **Storage Ring** | |
| Energy | 600 MeV or 750 MeV |
| Circumference | 53.2 m |
| RF Frequency | ~ 90.11 MHz |
| Harmonic Number | 16 |
| Max. Beam Current for FEL | ~ 100 mA/bunch |
| **Optical Klystron** | |
| Structure | Helical Optical Klystron |
| Number of Periods | 9 + 9 |
| Period Length | 110 mm |
| Length of Dispersive Section | 302.5 mm |
| K-value | 0.07 – 4.6 (Helical)<br>0.15 – 8.5 (Linear) |
| **Optical Cavity** | |
| Cavity Length | 13.3 m |
| Mirror | $HfO_2$, $Ta_2O_5$, $Al_2O_3$ multi-layer |
| **FEL Performance** | |
| Wavelength | 199 – 800 nm |
| Pulse Rate | 11.26 MHz CW |
| Spectral Width | ~ $10^{-4}$ |

## TI:SAPPHIRE LASER IN UVSOR

In UVSOR-II, Ti:Sapphire laser system has been installed. The laser system consists of a mode-locked oscillator (Mira; COHERENT), synchronized with the RF acceleration of the storage ring, and a regenerative amplifier (Legend; COHERENT). The centre wavelength is adjusted at 800 nm. The shortest laser pulse duration is 130 fs in FWHM and the maximum pulse energy of Legend is 2.5 mJ. The repetition rate of Legend's output is 1 kHz. In injection FEL experiment, output of Legend was used as external seed laser.

Figure 1 shows configuration of timing system of external laser for bunch slicing or coherent harmonic generation experiments. The electron bunch timing is synchronized with a certain phase of RF field in RF cavity of the storage ring. A part of RF field is picked up by a cavity pickup in the RF cavity and sent to timing



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system for the external laser. The pico-second or nano-second delay is adjusted by the phase shifter in Fig. 1. The RF signal is divided into two. One is for mode-locked oscillator and it is inputted to mode-lock controller named as Synchro-Lock. The controller synchronizes the timing of femto-second laser output with inputted RF signal. The other is for regenerative amplifier and 1-kHz signal is generated by combination of frequency divider. The 1-kHz signal is used for triggering a pump laser and Pockels cell in the amplifier. This laser timing system is also used for injection FEL operated in CW mode. We made small modification to use the timing system for Q-switched injection FEL.

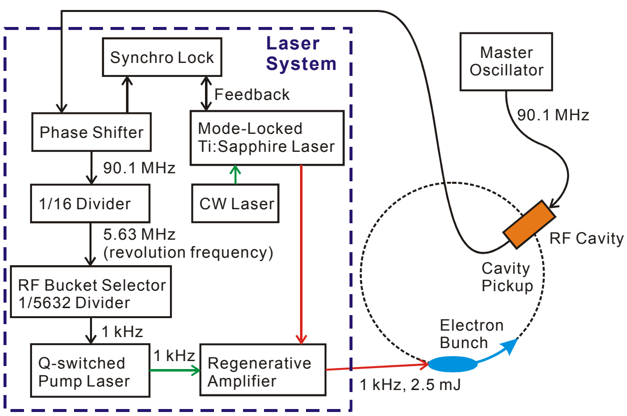


Figure 1: Configuration of timing system of laser for bunch slicing or coherent harmonic generation experiments.

## OPTICAL SYSTEMS FOR LASER INJECTION

Schematic diagram of developed optical system for injection FEL is shown in Fig. 2. To make sufficient injection of external laser to resonant cavity of FEL and efficient interaction between injected laser and electron bunch, wavelength and polarization matching, transverse and temporal overlap between external laser and FEL should be accomplished.

UVSOR-II FEL usually operates with circular polarization to avoid damages on resonator mirrors [6]. The tunable range of UVSOR-II FEL in circular polarization is from 199 to 461 nm at the beam energy of 600 MeV. We selected the FEL wavelength as 400 nm, second harmonics of Ti:Sapphire laser, which has been installed in UVSOR-II. And then, second harmonics of Ti:Sapphire laser was generated by a BBO crystal for wavelength matching between external laser and the FEL. In this setup, the polarization of output from the regenerative amplifier is linear and is transformed to circular polarization at quarter wave plate (QWP), before being injected. Under the condition, wavelength and polarization of external laser were successfully matched with FEL.

About the second issue, a monitor of transverse beam profile was prepared. In Fig. 2, beam sampler reflects both the FEL and external laser lights. Those lights are simultaneously measured by near field (NF) and far field (FF) camera. If profiles at far field and near field of both FEL and external laser beams are superposed, then the transverse mode of external laser is matched to the FEL cavity mode.

Concerning on the third issue, a part of reflected lights by beam sampler was sent to downstream of FEL cavity and measured by dual sweep streak camera (C5680; Hamamatsu). The timing of external laser was adjusted by changing phase shifter shown in Fig. 1 with observing time difference of FEL and external laser.

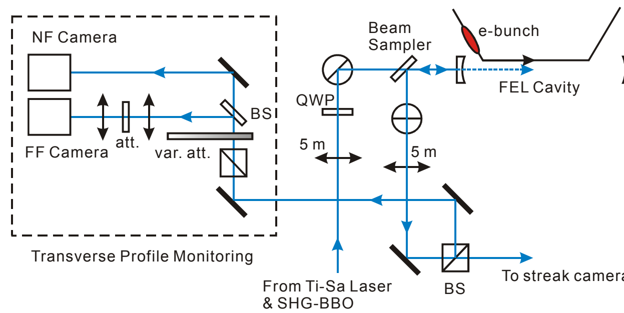


Figure 2: Optical setup for injecting external laser to SR-FEL oscillating at 400 nm and with circular polarization.

## Q-SWITCHING WITH I/Q MODULATOR

Three techniques have been developed for Q-switching of SR-FELs. First one is the gain modulation [7], second one is the modulation of RF frequency (RF-FM) [8,9] and the other one is the mechanical gating (chopper) [3] This time we employed second method because it does not require special mechanical equipments and has been employed in UVSOR FEL [9]. However RF-FM technique has serious problem on synchronization of external laser.

As previously mentioned, the external laser consists of a mode-locked oscillator and a regenerative amplifier. The oscillator has a system which synchronizes the oscillation frequency of the laser with external RF signal (90.1 MHz). For stable operation of the oscillator, stable RF signal should be supplied to the synchronization system. On the

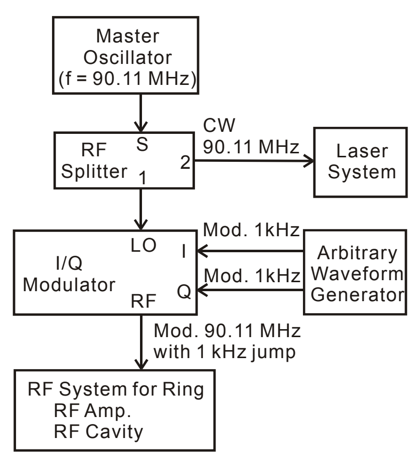


Figure 3: Block diagram of developed RF system. The laser system in this figure is same with in Fig. 1.

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other hand, RF frequency fed to RF cavity for driving storage ring should be modulated for Q-switching. An I/Q modulator is introduced for solving the problem. The developed RF system is shown in Fig. 3. We used a 90 MHz I/Q modulator (ZFMIQ-91M; MINICIRCUITS) and an arbitrary waveform generator (AFG3102; TEKTRONIX). The developed system enables us to operate the SR-FEL with Q-switching mode and injection of external laser. Details are described in following subsections.

### *Frequency Modulation with I/Q Modulator*

Diagram of typical I/Q modulator is shown in Fig. 4. At first, the RF signal inputted to LO port is divided into two with and without 90 degree phase shift. Second, the two RF signals are mixed with low frequency signals inputted to I and Q ports. Next, two mixed signals are summed up and outputted from RF port.

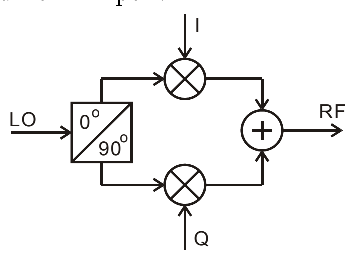


Figure 4: Block diagram of typical I/Q modulator.

When signals inputted to I and Q port are sin-wave and have same amplitude with 90-degree phase difference, the output signal from RF port can be calculated as

$$\begin{aligned} v_{\mathrm{RF}} &= \frac{V_{\mathrm{LO}} V_{\mathrm{I/Q}}}{2} \{\sin(\omega_1 t)\sin(\omega_0 t) + \cos(\omega_1 t)\cos(\omega_0 t)\} \\ &= \frac{V_{\mathrm{LO}} V_{\mathrm{I/Q}}}{2} \cos(\omega_0 - \omega_1)t \end{aligned} \quad (1),$$

where $V_{\mathrm{LO}}$ and $V_{\mathrm{I/Q}}$ is the amplitude of inputted signal to LO and I/Q port, and $\omega_0$ and $\omega_1$ are angular frequency of inputted signal to LO and I/Q port, respectively. As one can obviously see in Eq. 1, the outputted signal from RF port has angular frequency of ($\omega_0$- $\omega_1$). When we input pulsed sinusoidal wave to I and Q port as shown in Fig. 5, pulsed frequency modulation, which required for Q-switching FEL, is achievable.

To use the frequency modulation technique for injection FEL, two synchronization conditions should be achieved. One is synchronization between electron bunch and mode-locked oscillator. The other is synchronization between electron bunch and regenerative amplifier. By using I/Q modulator those conditions are achievable. Details are described in following subsections.

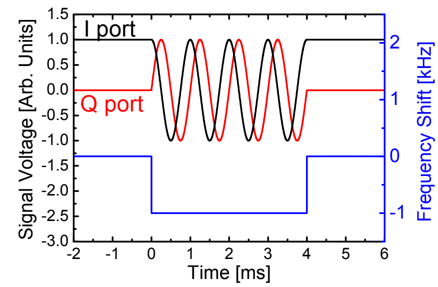


Figure 5: Input signal to I and Q port, and frequency shift of outputted signal from RF port.

### *Synchronization of Electron Bunch and Mode-Locked Oscillator*

The most useful aspect of I/Q modulation for Q-switching and injected FEL is controllability of phase. If we input certain voltages to I and Q port (for example, $V_{\mathrm{I}}$=1.0 V and $V_{\mathrm{Q}}$=0.0 V), the phase difference between RF signals of LO port and RF port can be uniquely defined. Therefore, if the input voltage to I and Q port after frequency modulation are adjusted same as before modulation, we can have same phase difference between LO port and RF port. It means electron bunch (synchronized with RF port signal) and external laser (synchronized with LO port signal) have same phase at 90.1 MHz before and after frequency modulation, even with very long modulation duration. The timing jitter caused by insertion of I/Q modulator was examined and determined as around 77 ps in FWHM, which is sufficiently smaller than electron bunch length (250 ps in FWHM).

### *Synchronization of Electron Bunch and Regenerative Amplifier*

By using I/Q modulator, the phase of electron bunch and external laser oscillator can be easily managed. However, we should be careful on another synchronization problem, which is synchronization between electron bunch and output of the regenerative amplifier of external laser. The 1-kHz trigger source of the amplifier is generated from one-sixteenth frequency (5.63 MHz) of master RF signal (90.1 MHz) without frequency modulation. The electron bunch circulates the storage ring with the one-sixteenth frequency (~5.63 MHz) of the master RF signal (~90.1 MHz) with modulation. The timing relationship between 1-kHz trigger signal and electron revolution before and after modulation should be same. To have such condition, number of waves of 5.63-MHz signals with and without frequency modulation during a modulation period should have relationship of

$$K_{\mathrm{Laser}} = m + K_{\mathrm{Bunch}} \quad (2),$$

where $K_{\mathrm{Laser}}$ and $K_{\mathrm{Bunch}}$ are the number of waves of 5.63-MHz signal for external laser (without modulation) and electron bunch (with modulation) during the period of



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frequency modulation respectively, $m$ is an integer. As one can see in Fig. 5, the modulation period $\Delta T$ should be multiple of one period of modulation frequency $\Delta f$ to achieve synchronization between electron bunch and mode-locked oscillator,

$$\Delta T = \frac{n}{\Delta f} \quad (3),$$

where $n$ is an integer. Then the $K_{\mathrm{Laser}}$ and $K_{\mathrm{Bunch}}$ can be expressed as

$$K_{\mathrm{Laser}} = \Delta T \frac{f_0}{16}, \quad K_{\mathrm{Laser}} = \Delta T \frac{f_0 - \Delta f}{16} \quad (4),$$

where $f_0$ is the frequency of RF signal. By substituting Eq. 4 to Eq. 2, we obtain

$$\begin{aligned} \Delta T \frac{f_0}{16} &= m + \Delta T \frac{f_0 - \Delta f}{16} \\ m &= \frac{\Delta T \Delta f}{16} = \frac{n}{16} \end{aligned} \quad (5).$$

If we select the condition of $\Delta f = 1$ kHz, then the shortest modulation period can be given as $\Delta T = 16$ ms (condition of $m = 1$ and $n = 16$). This limits the maximum repetition rate of the Q-switched injection FEL by using I/Q modulator. In practical experiment, we selected those parameters as $\Delta T = 96$ ms, n = 96 and $\Delta f = 1$ kHz.

## EXPERIMENTAL RESULT

Injection FEL experiments were conducted with developed systems. Figure 5 shows the typical result of Q-switching FEL with and without laser injection. By laser injection, the pulse duration of Q-switched FEL get narrower than without injection. This means that the developed systems successfully worked well and we succeeded in injecting external laser to SR-FEL.

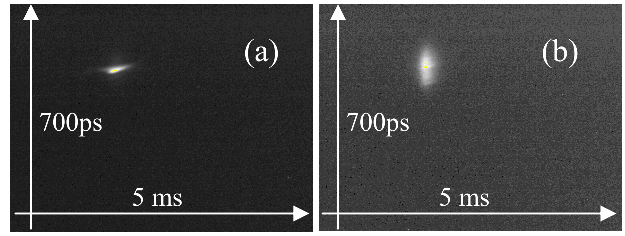


Figure 5: Temporal structure of Q-switched FEL taken with dual sweep streak camera. (a) with laser injection (b) without laser injection.

## SUMMARY

Optical and RF systems for injection FEL (CW and Q-switched) have been developed. The wavelength and polarization matching of SR-FEL and external laser was accomplished by the developed optical system. The optical system also enabled us to ensure transverse and timing overlap between two lasers. The developed RF system using I/Q modulator enables us to synchronize the external laser with electron bunch in Q-switched operation of SR-FEL. These developments have been contributed to achieve mastering the SR-FEL dynamics by external laser and enhancing the CSR intensity with Q-switched injection FEL [4, 5].

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