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# ELECTRONIC MODULATION OF THE FEL-OSCILLATOR RADIATION POWER DRIVEN BY ERL

O. A. Shevchenko†, S. V. Tararyshkin, Ya. V. Getmanov[1], S. S. Serednyakov[1], E. V. Bykov, Budker Institute of Nuclear Physics, Novosibirsk, Russia,
A. Melnikov[1], M. Fedin, S. Veber[1], International Tomography Center SB RAS, Novosibirsk, Russia,
[1]also at Novosibirsk State University, Novosibirsk, Russia

## *Abstract*

FEL oscillators usually operate in CW mode and produce periodic train of radiation pulses but some user experiments require modulation of radiation power. Conventional way to obtain this modulation is using of mechanical shutters but it cannot provide very short switching time and may lead to decreasing of the radiation beam quality. Another way could be based on the electron beam current modulation but it cannot be used in the ERL. We propose a simple way of fast control of the FEL lasing which is based on periodic phase shift of electron bunches with respect to radiation stored in optical cavity. The phase shift required to suppress lasing is relatively small and it does not change significantly repetition rate. This approach has been realized at NovoFEL facility. It allows to generate radiation macropulses of desirable length down to several microseconds (limited by quality factor of optical cavity and FEL gain) which can be synchronized with external trigger. We present detailed description of electronic power modulation scheme and discuss the results of experiments.

## INTRODUCTION

Novosibirsk Free Electron Laser (NovoFEL) facility comprises three FELs, which use energy recovery linac (ERL) as a source of electrons [1]. All three FELs are FEL oscillators. They operate in CW mode and produce periodic train of radiation pulses. Energy recovery allows to achieve very high averaged current of the electron beam which results in high average power of radiation. There are applications where this power is really needed [2] but most often it has to be attenuated. In some experiments users want to have large peak power and to avoid overheating of their samples at that [3]. This demand can be fulfilled by modulation of FEL radiation. For this purpose one can think of mechanical shutter but this shutter cannot be done to be fast enough and it also disturbs transverse profile of radiation.

Ideal solution of this problem would be to instantly turn on and off the FEL lasing process. For the single pass FEL based on linear accelerator the lasing can be controlled by the beam injection [4]. In ERL, injection is required to operate in CW mode; it is not possible to switch it on and off instantly. Particularly, for the case of NovoFEL accelerator, beam loading effects in the accelerating structure are very significant because of high average current: fast switching of the current leads to transient effects resulting in beam loss. Instead of that, more “delicate” approach should be developed that keeps the electron beam current almost constant, but efficiently suppresses the lasing in FEL. In this work we developed and implemented at NovoFEL the approach that allows to generate the THz macropulses at any repetition rate and almost any individual length from several seconds and down to several microseconds (the minimal pulse duration is determined by growing up and decay time of lasting which depends on the FEL gain and the quality factor of the optical cavity). This regime has been examined at all three FELs by generation of macropulses with tens of microseconds duration. Possible applications of the electronic modulation of THz radiation are discussed in this paper.

## IMPLEMENTATION OF ELECTRONIC POWER MODULATION

In FEL oscillator lasing is possible only when radiation and electron bunches come to undulator simultaneously. In other words electron bunch repetition rate has to be almost equal to the round-trip frequency of the optical cavity (usually acceptable detuning does not exceed $10^{-4}$). Changing repetition rate by about 1% will certainly stop lasing, at the same time corresponding variation of the average beam current is not significant and can be easily tolerated by the accelerating structure of ERL. Bunch repetition rate is determined by the frequency of the master oscillator which signal is also used as an input for RF generators. This frequency cannot be changed very fast. Fortunately there is another approach which results in the change of repetition rate and in the termination of lasing.

If injection of one electron bunch is delayed by, e.g., one period of the RF accelerating field it almost does not influence on beam dynamics in accelerator but this bunch comes to undulator in wrong time and does not interact with THz wave, which stops its amplification and leads to fast decay of radiation power. To prevent the formation of new THz wave, injection phase has to be shifted periodically, which actually leads to the small decreasing of the repetition rate.

### *Implementation Scheme*

The scheme of practical implementation of the injection phase shifting is shown in Fig. 1. Injection is triggered by trigger signal modulator, which counts the pulses coming from the master clock. Pulses come with the repetition rate equal to RF accelerating field frequency 180.4 MHz. The simplest algorithm of the trigger signal modulator operation is the following: it bites N-1 successive pulses out of the 180.4 MHz pulse sequence and then triggers injection with the next $N^{th}$ pulse (for the 1st FEL N = 32, for the 2nd FEL N = 24 and for the 3d FEL N = 48). In normal regime

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† email address O.A.Shevchenko@inp.nsk.su

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(CW) the phase shifter is switched off, while in power modulation mode it is on. The phase shifter operation algorithm is the following: it periodically bites each K$^{th}$ pulse out of the 180.4 MHz pulse sequence which results in the shift of injection phase by one RF period. The smaller values of K used, the better suppression of FEL lasing is achieved. On the other hand, K should be large enough to avoid influence on accelerator operation. It was shown experimentally that K = 100 is sufficient to suppress FEL lasing completely without influencing the accelerator operation.

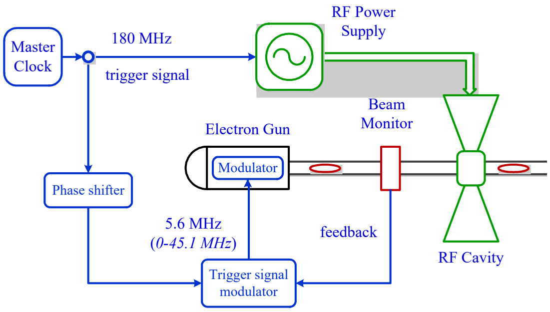

Figure 1: Layout of the injection phase shifting system.

### Resulting Time Structure of FEL Radiation

A typical example of time dependence of the first FEL radiation is shown in Figure 2. In the normal operation regime (CW) this structure is a continuous train of short radiation pulses (50-100 ps), which follow each other with the frequency of ~ 5.6 MHz determined by the optical cavity length.

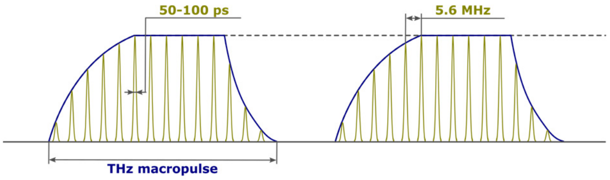

Figure 2: Schematic view of NovoFEL radiation macropulses. The length of the individual THz pulse and their repetition rate are shown for 1$^{st}$ FEL.

When NovoFEL operates in the power modulation mode, the laser radiation consists of macropulses with minimal duration about 10 µs and arbitrary repetition rate which is controlled by user. Each macropulse contains tens of individual THz radiation pulses and its fronts depend on the FEL gain (pulse raise) and the quality factor of the optical cavity (pulse decay). The characteristic rise and decay time is about 2 µs.

There are two regimes of the phase shifter control. In the first fully digital regime user sets duration of time intervals during which the shifter is turned on and off. In this regime one gets periodic train of radiation macropulses. In the second regime the shifter is normally turned on, so that the lasing is suppressed. It is turned off by external triggering signal for the digitally set time duration. In this regime one can get single macropulses, which can be synchronized with user equipment.

## RESULTS AND DISCUSSIONS

### Generation of Macropulses at NovoFEL

In order to demonstrate the possibilities of electronic modulation system (EMS), we recorded the THz macropulses with different pulse length at all three FELs of NovoFEL, which correspond to different energy ranges of available radiation. Macropulses of THz radiation with different length in the range of 10 µs to 40 µs obtained at 130 µm wavelength (1$^{st}$ FEL) are shown in Fig,3. Pulses with duration of more than 400 µs are also available, but they do not have any direct practical implementations except for the aim of keeping a stable average power over a long period of time in CW experiments (see below).

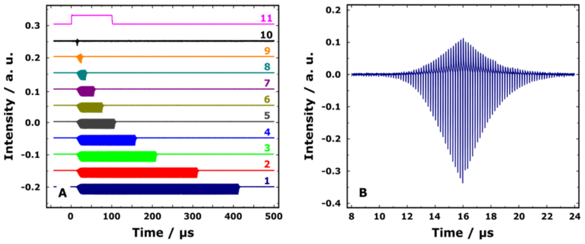

Figure 3: (A) Macropulses of THz (130 µm) radiation Durations are (1) 400 µs; (2) 300 µs; (3) 200 µs; (4) 150 µs; (5) 100 µs; (6) 70 µs; (7) 50 µs; (8) 30 µs; (9) 20 µs; (10) 10 µs (multipled by 10); (11) trigger signal. Each subsequent pulse is vertically shifted; (B) Macropulse with 10 µs duration. The individual pulses of THz radiation with the frequency of 5.6 MHz are clearly visible.

Fig. 3 (B) shows the rising and falling edges of the shortest obtained macropulse. The time resolution of the detector used at the first FEL (Fig. 3 B) is enough to see the fine structure of THz macropulse, which consists of the series of short individual pulses at electron beam repetition rate.

### Measurement of the FEL Parameters

From the analysis of THz macropulse edges one can obtain characteristic rise and decay time and calculate FEL gain and round-trip losses in optical cavity. An example of such calculation is shown in Fig. 4 and Fig. 5.

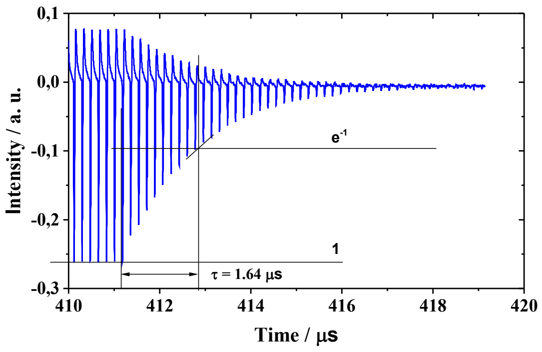

Figure 4: Calculation of losses for the first FEL optical cavity. Characteristic decay time is 1.64 µs, round-trip losses are 10.3 %.

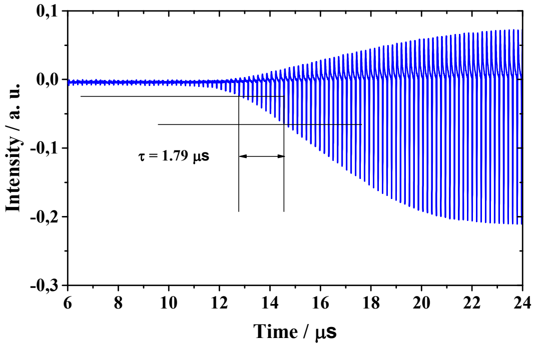

Figure 5: Gain calculation for the first FEL. Characteristic rise time is 1.79 μs, gain exceeds losses by 9.5 %.

Obtained parameters are in reasonable agreement with previously made calculations [5].

## POSSIBLE APPLICATIONS OF ELECTRONIC MODULATION OF THZ RADIATION AT NOVOFEL

Electronic modulation system at NovoFEL provides unique possibilities for controlling and tuning average power of THz radiation and repetition rate of THz macropulses directly on the user stations. The possible applications of EMS used in experiments with THz radiation include the following options: (i) controlling of average THz power over the long time period; (ii) formation of short macropulses with highest peak power available; (iii) lock-in detection.

### *Control of the Average THz Power in CW Experiments*

In order to precisely measure the influence of CW THz radiation on different objects it is crucial to have a stable average THz power over a long period of time (hours), which due to working principles of NovoFEL is quite challenging task. Indeed, the generation of THz radiation is determined by fine tuning of a number of different parameters that are sensitive to the long time stability of electron beam, heating of optical resonators and other parts, etc. In turn, using EMS the desired power can be achieved by measuring the average power in real time and then automatically adjusting the number of electron beam pulses with shifted frequency that suppress lasing. For optimal performance, the working average power should be approximately two times lower than the peak power available at the moment in order to have an amplification reserve.

Reduction of the average power may be also very useful for adjustment of the accelerator as it allows to reduce beam loses at the recuperation stage.

### *Formation of Short High-power THz Macropulses*

In addition to studying the cumulative effects of THz on various objects, EMS allows one to routinely perform time resolved experiments with a time resolution determined by the shortest available THz macropulse. As it can be seen from Fig. 3, 10 μs THz pulses are reachable with typical amplification coefficients of the optical resonators of NovoFEL. Apart from resolution in time, the use of macropulses decreases the average THz power of NovoFEL, but keeps its peak value. Such a control of radiation power is important in practically every experiment, because of a possibility to irreversible damage the sample under study. It should also be noted that the impact of individual THz pulses on the sample in the microsecond macropulse can be investigated, which further extend the temporary resolution of the experiment.

### *Lock-in Detection*

EMS can be used in experiments utilizing lock-in detection schemes where the modulation of THz power at certain frequency is required. The repetition rate of THz macropulses, which is set by frequency generator directly at the user stations, can be used for lock-in detection of the modulated signal. Since NovoFEL can be operated in CW mode, there is no low frequency limit for macropulse repetition rate. The upper limit is mainly determined by the rise and decay times of the FEL optical resonator and corresponds to 10-50 kHz. The advantage of using lock-in detection scheme offered by EMS is a possible increase in the signal to noise ratio of measured values.

## CONCLUSION

In this work an approach for the creation of THz macropulses at any repetition rate and almost any individual pulse length were developed and implemented at NovoFEL. Suggested radiation electronic modulation system is based on periodic shift of the phase of electron bunch injection. Such a shift suppresses lasing and forms macropulses from quasi-continuous radiation of NovoFEL. The system is directly embedded into the electronic infrastructure of NovoFEL and can be triggered directly on user stations. For users such electronic modulation system provides a unique possibility, e.g., to control the average power of THz radiation over a long period of time or to create macropulses with as short as 10 μs duration.

In order to characterize EMS, series of macropulses with different durations from 10 to 400 μs were measured for three available frequency ranges. Using the rising and falling edges of typical macropulses the calculations of the gain and total losses were done. Obtained characteristics are in a good agreement with the data obtained earlier.

## ACKNOWLEDGEMENTS

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