A PROPOSAL OF SHORT X-RAY PULSE GENERATION FROM COMPRESSED BUNCHES BY mm-WAVE iFEL IN THE SPRING-8 UPGRADE PLAN

M. Masaki*, K. Fukami, C. Mitsuda and T. Watanabe,
JASRI/SPring-8, 1-1-1 Kouto, Sayo, Hyogo, 679-5198, Japan

Abstract

Electron bunches in storage rings could be constantly-compressed less than 1 ps (r.m.s.) by a millimeter wave inverse free electron laser (mm-iFEL) system which is composed of a helical wiggler with long period length and a mm-wave corrugated waveguide resonator. Simulation studies show that the mm-iFEL leads to the equilibrium bunch length of 0.6 ps (r.m.s.), when a bunch charge is 479 pC corresponding to bunch current of 0.1 mA. To work the mm-iFEL system, ultra short bunches injected from the XFEL/SACLA C-band linac are indispensable.

INTRODUCTION

Main goal of the SPring-8 upgrade plan [1] is to attain diffraction-limited hard X-ray sources in the photon energy region of 10 keV by reducing electron beam emittance to several tens of pm·rad. In addition, we have a plan to prepare short pulse options for time-resolved experiments of pico-second order with high repetition rate. CW short X-ray pulses from a storage ring have very wide frequency range and will allow us to observe dynamical evolutions of microscopic systems in various time scales of pico- to several seconds. Especially, the time range of pico-second or less will be of essential importance for temporal resolution of novel pump-and-probe experiments such as a method using synchronization with the XFEL/SACLA so-called X-ray pump and X-ray probe experiments. The best scenario is that selected bunches have equilibrium bunch length of 1 ps or less. A millimeter wave storage-ring iFEL [2] may be one possible solution for it. If resonant wavelength of the FEL is a few millimeters, which is about ten times longer than typical short bunch length of 0.3 mm corresponding to 1 ps, almost all electrons of a bunch could be confined in one valley of ponderomotive potentials formed by the FEL mechanism. As a result, a bunch captured in the mm-wave "RF bucket" will stay in a compressed state. We have studied the bunch compression effects of the mm-iFEL by simulations. In this paper, results of the simulations are reported with main apparatuses of the mm-iFEL and the indispensable short bunch injection from the XFEL/SACLA.

MAIN APPARATUSES OF THE MM-WAVE IFEL SYSTEM

The mm-iFEL system consists of a helical wiggler as a mm-wave radiator and a waveguide resonator to accumulate the radiated mm-wave. The helical wiggler has to have the deflection parameter of several hundreds to radiate the mm-wave at a multi-GeV ring such as the SPring-8. Since the wiggler period length becomes several meters, its total length reaches to about 20 m even if the period number is about 4. The parameters of the helical wiggler we consider at present are shown in Table 1.

Table 1: Parameters of the Helical Wiggler

peak magnetic field [T]	1
period length [m]	3.84
deflection parameter K	360.7
period number	4
resonant wavelength in free space [mm]	1.81

A mm-wave waveguide resonator (MWR) with mirrors of both ends needs to have a feature of very low propagation loss. Corrugated waveguides [3, 4] may be useful for it. Its inner wall surface has submillimeter-scale corrugation structure along the circumferential direction. The fundamental propagation mode is HE_{11} mode which attenuation in the waveguide is very small due to almost no wall current, and the electric field distribution of the HE_{11} mode resembles that of the Hermite-Gaussian mode (TEM_{00}). The resonant wavelength λ_{rg} in the waveguide gets longer than that in the free space and is expressed by the following formula,

$$\lambda_{rg} = \frac{2{\gamma_z}^2\left\{1-\sqrt{1-\frac{1}{{\gamma_z}^2}\left[1+\frac{1}{2}(\frac{\lambda_w p}{b})^2\right]}\right\}}{1+\frac{1}{2}(\frac{\lambda_w p}{b})^2}\lambda_{r0}, \quad (1)$$

where ${\gamma_z}^2 = (1-{\beta_z}^2)^{-1}$, $\beta_z = \beta(1-K^2/2\gamma^2)$, K is the deflection parameter of the helical wiggler, β is electron velocity relative to light speed, γ is electron energy divided by its rest mass $m_e c^2$, b is aperture size of the square waveguide, and λ_{r0} is the resonant wavelength in free space. The parameter p is the normalized transverse wavenumber which is close to one for the HE_{11} mode, when the corrugation depth is nearly equal to $\lambda_{r0}/4$ which gives the theoretical minimum attenuation. The helical wiggler mentioned above and the corrugated waveguide summarized in Table 2 give the resonant guide wavelength λ_{rg} of 3.06 mm. The conversion efficiency of the wiggler radiation into the HE_{11} mode is roughly estimated to be about 10 % of the in-

* masaki@spring8.or.jp

tegrated power of the resonant mm-wave radiation in free space [5].

Table 2: Corrugated Waveguides under Consideration

propagation mode	HE_{11}
frequency [GHz]	165.5
guide wavelength [mm]	3.06
cross-sectional size [mm]	85×85
corrugation	
pitch [mm]	0.8
width [mm]	0.6
depth [mm]	0.4
power loss [dB/m]	1.6×10^{-5}
waveguide material	copper

SHORT BUNCH INJECTION FROM THE XFEL/SACLA C-BAND LINAC

To capture a short bunch in one mm-wave bucket generated by the mm-iFEL, an injection beam is required to be shorter than 1 ps. The XFEL/SACLA C-band linac will be very useful for the ultra-short bunch injection. To transfer the short bunch to the storage ring without lengthening, XFEL-to-Storage Ring beam transport line needs to be designed to suppress the dispersions, which cause bunch lengthening through the broadening of original energy spread due to the coherent synchrotron radiation (CSR). The beam transport line designed on the basis of Chasman-Green lattice is one of the candidates [6]. Calculations using a tracking code "elegant"[7] show that the beam is transported without extreme bunch lengthening, when a bunch charge is 479 pC. The root-mean-square (r.m.s.) bunch length and relative energy spread at an injection point of the storage ring are about 0.76 ps and 0.19 %, respectively (see Fig. 1).

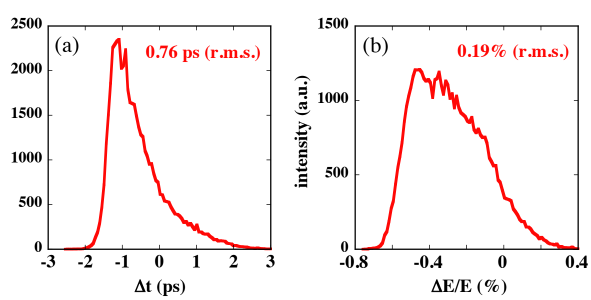

Figure 1: (a) Temporal and (b) momentum bunch profiles at an injection point of the storage ring after passing through the designed XFEL-to-Storage Ring transport line. The calculations include the CSR effect when a bunch charge is 479 pC.

SIMULATION RESULTS

Requirement for mm-Wave Peak Power

In order to keep the equilibrium bunch length shorter than 1 ps, the pondermotive potential of the mm-iFEL needs to be very strong to beat a wake potential derived from the CSR which causes the energy spread broadening of compressed bunches. The required peak power of the mm-wave potential is estimated by simulations, in which the storage ring parameters of the sextuple-bend lattice [8] for the SPring-8 upgrade plan and electron energy of 6 GeV are assumed. A main RF system of 508.58 MHz is also needed to compensate radiation loss by bending magnets and undulators. A mm-wave zero-cross timing where the electron bunch is compressed should be set near the synchronous phase of the main RF. According to the simulation studies with the CSR effect at bunch charge of 479 pC, the short bunch injected from the XFEL/SACLA is confined in one mm-wave bucket and kept shorter than 1 ps (r.m.s.) even after several thousand turns from the injection (see Fig. 2), when the mm-wave peak power of 1.8 GW is accumulated in the MWR. Figure 3a shows the longitudinal phase space distribution at 16000 turns after the injection, where the bunch stays in a compressed state of 0.6 ps (r.m.s.). However, the relative energy spread increases from 0.15 % (r.m.s.) to 0.3 % (r.m.s.). If the peak power is insufficient, a portion of electrons in a bunch which should be normally confined in the specified mm-wave bucket will be trapped in the adjacent wrong buckets (see Fig. 3b). The simulations roughly include the effect of emittance growth due to the intra beam scattering (IBS) and radiation excitation by the helical wiggler itself. Fortunately, the emittance growth of several hundreds of pm·rad has an insignificant effect on the simulation results, since it is negligibly-small compared with the intrinsic emittance $\lambda_{r0}/4\pi$ of the mm-wave wiggler radiation. The bunch compression by the mm-iFEL has advantages for the peak brilliance and partial flux in comparison with bunch slicing techniques, regardless of the large emittance growth. At bunch current of 0.1 mA, the peak brilliance could reach to 5×10^{25} (photons/sec/mm^2/mrad^2/0.1%b.w.).

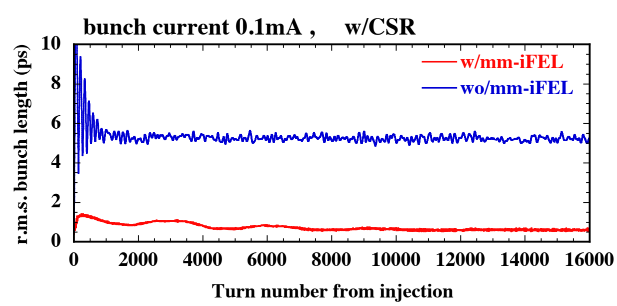

Figure 2: Turn-by-turn bunch lengths after the injection. Red and blue lines show those with and without the mm-iFEL accumulating the peak power of 1.8 GW, respectively.

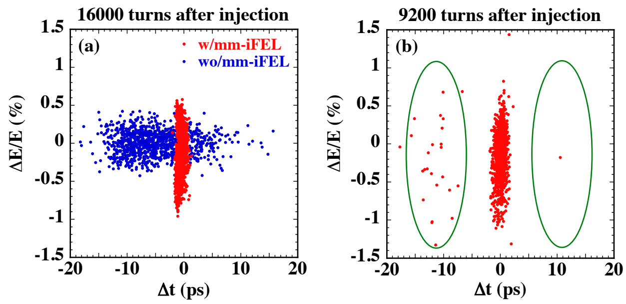

Figure 3: (a) Longitudinal phase space distributions at the 16000 turns after the injection. Red and blue dots show those with and without the mm-iFEL when the peak power is 1.8 GW. (b) The phase space distribution with the mm-iFEL when the peak power is 1.6 GW. The electrons in the green circles are spilt out of the middle specified mm-wave bucket.

mm-Wave Power Accumulation Scheme

The peak power of about 2 GW could be step-by-step accumulated by several tens of mm-wave drive bunches with a few pico seconds or less (see Fig. 4), the role of which could be played by the short bunches compressed using the 3.5th harmonic RF system considered in the upgrade plan [1]. The drive bunches with small charges would be preferable to reduce the CSR effect. The mm-wave power loss per one round trip in the MWR is estimated to be 0.3 % in the case of the theoretical waveguide loss and reflectivity of the copper mirrors of both ends. The Giga-watt waveguide resonator with the small power loss will be one of the technical issues of the mm-iFEL system. If the power loss becomes a problem, an external source such as a mm-wave gyrotron may be necessary to compensate the loss.

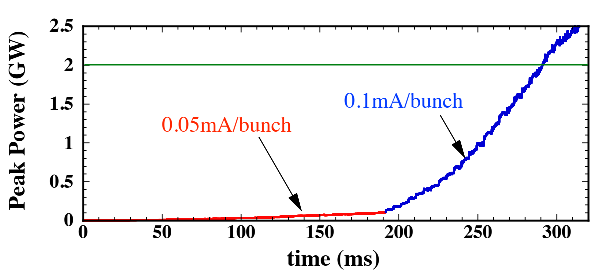

Figure 4: Simulated peak power growth in the MWR by drive bunches with bunch length of about 3 ps (r.m.s.). Red and blue lines show the power growth from zero to 0.11 GW by the drive beam with 0.05 mA/bunch and from 0.11 GW to 2.0 GW by those of 0.1 mA/bunch, respectively. The drive bunch numbers are increased one-by-one every 4.79 ms corresponding to1000 turns.

SUMMARY

For the short X-ray pulse generation as an option of the SPring-8 upgrade plan, we have studied the mm-iFEL which is one of the candidates to store sub-picosecond bunches in the ring. The simulations show promising results for the bunch compression effect of the mm-iFEL. However, we have not yet addressed some technical issues of the main apparatuses such as the ultra low loss waveguide resonator of mm-wave. Since the emittance growth of the compressed bunch itself is unavoidable, we may need to have a basic strategy to shorten selected electron bunches only. In that case, the short bunches will be captured in some specified RF buckets to share with other buckets for the untouched ultra low emittance bunches. A possible layout for it may be to place the mm-iFEL system on a dedicated bypass line which is assumed to be installed inside the storage ring and parallel to the long straight section (see Fig. 5). And a pair of fast kickers will be also necessary to steer the selected bunches to the iFEL system. In any case, we will have to study the technical issues that need to be overcome and the feasibility of the mm-iFEL, including possibilities of other better methodologies to generate the short X-ray pulses in the storage ring.

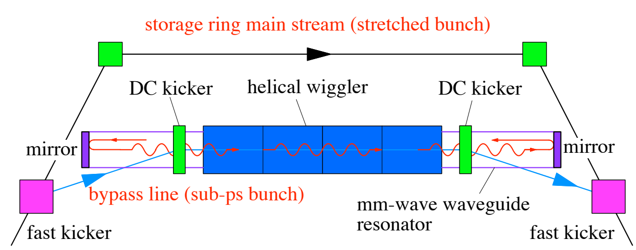

Figure 5: A possible layout of the mm-iFEL system placed on a bypass line assumed to be inside the storage ring and parallel to the long straight section.

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