HIGH GAIN FEL WITH A MICRO-BUNCH STRUCTURED BEAM BY THE TRANSVERSE-LONGITUDINAL PHASE SPACE ROTATION

M. Kuriki*, Y. Seimiya, HU/AdSM, Higashihiroshima
R. Kato, ISIR, Osaka
H. Hayano, K. Ohmi, KEK, IBaraki
S. Kashiwagi, Tohoku University, Sendai

Abstract

FEL is one of the ideal radiation source over the wide range of wavelength region with a high brightness and a high coherence. Many methods to improve FEL gain has been proposed by introducing an active modulation on the bunch charge distribution. The transverse-longitudinal phase-space rotation is one of the promising method to realize the density modulation as the micro-bunch structure. Initially, a beam density modulation in the transverse direction made by a mechanical slit, is properly transformed into the density modulation in the longitudinal direction by the phase-space rotation. That results the longitudinal micro-bunch structure. The micro-bunch structure made with this method has a large tunability by changing the slit geometry, the beam line design, and the beam dynamics tuning. A compact FEL facility based on this method is proposed.

INTRODUCTION

In recent years, an extremely short bunch electron beam generation by employing short pulse laser and photo-cathode is one of the hottest topic in electron linac. The temporal scale is less than 1 ps and is approaching to as (1.0×10^{-18}) level. The extremely short electron beam is useful as a driver of coherent radiation, a probe to fast phenomena, etc. As we mentioned already, such short pulse electron beam is usually generated by photo-cathode technology with a short pulse laser. In this case, however, the time structure of the generated bunch is limited by temporal response of the cathode (some material has a long tail in the electron emission). Although once we succeeded the generation, we have to fight against de-bunching phenomena by space-charge effect. In this article, we discuss a totally different approach to generate such extremely short bunch. In addition, we also propose to generated a micro-bunch structure which enhances the coherent radiation effectively.

In our approach, a moderate brightness electron beam is generated by ordinal photo-injector technology, i.e. a short pulse in order of several ps with a photo-cathode and boosted up to more than 100 MeV. By a bunching method, the bunch is shorten down to 1 ps full width. Such kind of bunch can be generated by employing ordinal technologies. Figure 1 shows EEX (Emittance EXchange) beam line which rotates the beam in X-Z phase-space. A part of bunch is clipped by a mechanical slit which limit the spatial distribution of the bunch in transverse space as shown figure. The transverse spatial modulation by the slits is transferred to the longitudinal modulation by the X-Z phase space rotation as shown in the figure. If the slit is a narrow single slit, an extremely short bunch can be obtained. If the slit is equi-distant multi-slits, a micro-bunch structure in the longitudinal space is obtained.

* mkuriki@hiroshima-u.ac.jp

PHASE SPACE ROTATION

Here, we explain the foundation of the X-Z rotation with EEX beam line. The phase-space rotation is initially proposed for optimization for efficient FEL[1][2]. Transfer matrix of the first dogleg in X-Z phase space is given by

$$\mathrm{M}_D(\eta,\xi,L) = \begin{bmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{1}$$

where L is the length of the dogleg, η and ξ are dispersion and momentum compaction of the dogleg. η and ξ are given with geometry of the dogleg as

$$\eta = S_1\frac{\sin\alpha}{\cos\alpha^2} + 2\frac{D}{\sin\alpha}\left(\frac{1}{\cos\alpha} - 1\right) \tag{2}$$

$$\xi = S_2\frac{\sin\alpha^2}{\cos\alpha^3} + 2\frac{D}{\sin\alpha - \alpha}, \tag{3}$$

where D and S_1 are pole length of a bending magnet and its interval, α is the bending angle. The transfer matrix of the TM_{210} cavity is given in the thin-lens approximation as

$$\mathrm{M}_C(k) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{bmatrix}, \tag{4}$$

Particle transfer through EEX beam line is given by product of these matrices as

$$\mathrm{M}_{EX}(\eta,\xi,L,k) = \mathrm{M}_D\mathrm{M}_C\mathrm{M}_D, \tag{5}$$

and a matching condition give as

$$1 + \eta k = 0, \tag{6}$$

greatly simplifies the result given as

$$\mathrm{M}_{EX} = \begin{bmatrix} 0 & 0 & -L/\eta & \eta - L\xi/\eta \\ 0 & 0 & -1/\eta & -\xi/\eta \\ -\xi/\eta & \eta - L\xi/\eta & 0 & 0 \\ -1/\eta & -L/\eta & 0 & 0 \end{bmatrix}, \tag{7}$$

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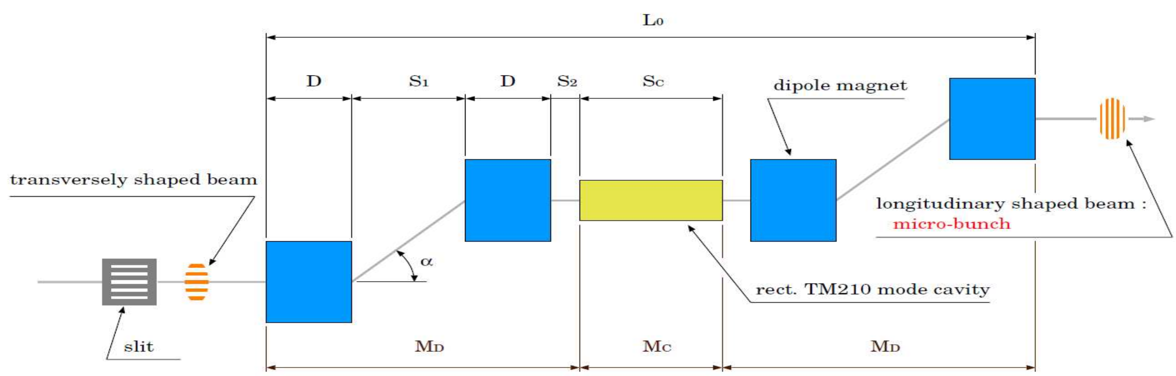

Figure 1: Schematic view of the EEX (Emittance EXchange) beam line which consists from two dogleg sections and one TM_{210}mode cavity. By passing a beam through the beam line, x and z phase-space distribution of the beam is exchanged by X-Z phase-space rotation.

where X and Z phase space distributions are exchanged by EEX, i.e. X distribution after EEX depends only on Z before EEX, and vise versa. From this feature, if we make any modulation on the transverse particle distribution, it can be transferred to the longitudinal space by EEX. If the modulation is clipping by a narrow slit in x space, it becomes very short bunch in z space after EEX, i.e. an extremely short bunch can be obtained. If the modulation is by multi-slits with equi-distance, a micro-bunch structure is appeared in z space after EEX. Comparing with the ordinal short bunch formation with photo-cathode and short-pulse laser, it is more vital against to space charge, since we can make the modulation after acceleration. In addition, the bunch structure can be easily changed by changing the slit geometry. EEX has such advantages and can be applicable various purpose.

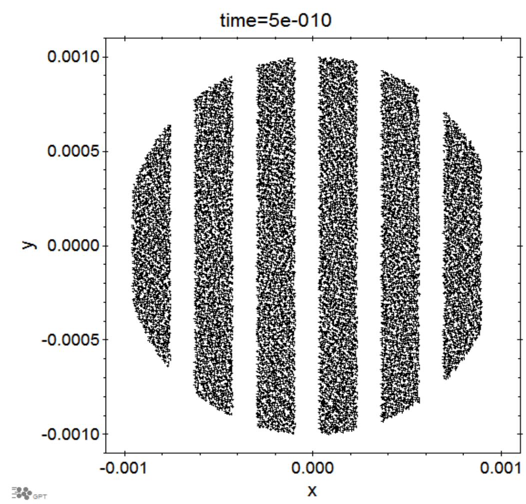

Figure 2: Initial beam distribution after the clipping by the slits.

HIGH GAIN FEL WITH A MICRO-BUNCH STRUCTURE

As an application, we consider high gain FEL with a micro-bunch structure. FEL is a well known process which radiates high coherent synchronous radiation light from undulator. In FEL, a micro-bunch structure in a bunch has an important role for efficient and coherent radiation. In SASE FEL, the micro-bunch structure is triggered by fluctuation in the bunch intensity and the FEL gain is increased as the micro-bunch structure is grown. Several techniques which introduce artificial micro-bunch modulation for an efficient FEL, like HGHG[3], EEHG[4], etc. In this article, we introduce a micro-bunch structure by clipping the beam with slits in transverse direction and transferred to the longitudinal space by phase-space rotation. For the phase-space rotation, EEX described in is assumed. Initial beam dimension in the transverse space is shown in Fig. 2. The beam size is 1 mm in radius with $2.0 \times 10^{-6}\mathrm{m.rad}$ emittance and the beam energy is 150 MeV. The bunch length is 1 ps in full width. The slit width is 200μm and the interval is 330 $\mu\mathrm{m}$. The dipole-mode cavity is S-band TM_{210} rectangular cavity. The peak E-field is $25.9MV/m$. The length of the cavity is 315 mm. The B-field is shown in Fig. 3. The height shows B_y normalized by the peak value and two horizontal axes are x and y normalized with the cavity size, respectively. 0.5 in the horizontal axes correspond to the cavity center. B_y is peaked at the center of the cavity.

Figure 4 shows particle distribution after EEX beam line in $z-\gamma$ plane. The spatial modulation made in x direction by the slits is appeared in longitudinal space as a result of the phase space rotation, but the energy modulation along z position is recognized. This energy modulation is not suitable for FEL and compensated by three C-band accelerating structure. Simultaneously, we try to decelerate the beam energy to observe FEL enhancement by the micro-bunch structure easily. For that purpose, the beam is set not on zero-cross, but on the decelerate phase. Figure 5 shows the particle distribution in $z-\gamma$ plane after the deceleration. The energy becomes 25 MeV and the energy spread is increased 0.4% (RMS). The micro-bunch structure whose

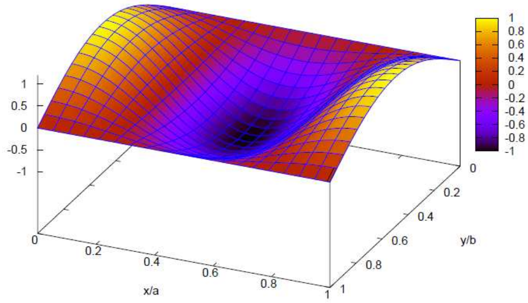

Figure 3: B_y normalized by the peak vale of the dipole mode TM_{210} cavity is shown in x-y plane. X and Y are also normalized with the cavity dimension in each direction and 0.5 corresponds to the center.

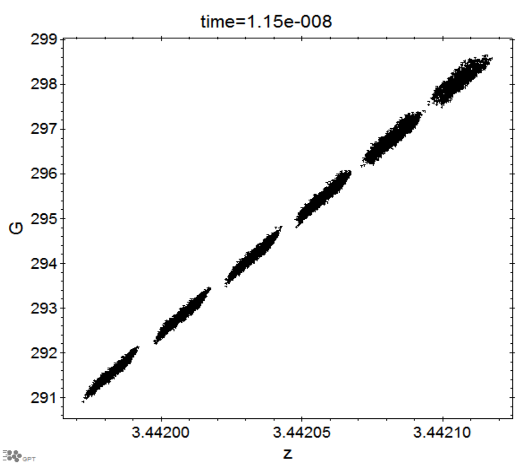

Figure 4: Particle distribution in $z-\gamma$ plane after EEX beam line.

interval is $26\mu m$ is observed. By assuming 60 mm undulator period and $K = 1.08$, undulator radiation wave-length can be same as the micro-bunch interval, $26\mu m$.

Figure 6 shows the FEL gain curve as a function of the undulator length. The undulator parameter is 60 mm period and $K = 1.08$. To simulate SASE amplification, input power is set 1 nW. The red circle shows results with the micro-bunch modulation. As a reference, we perform the same calculation, but without the modulation. The blue circle shows results without the micro-bunch modulation. There were no significant enhancement on FEL gain.

SUMMARY

Phase-space rotation gives a wide variety of operability on the beam and transverse and longitudinal EEX is an example. EEX with transverse spatial modulation with slits is applicable to generate an extremely short bunch and micro bunch structure which is very useful as a probe for fast phenomena, coherent radiation driver, etc. As an example, FEL gain enhancement with the micro-bunch structure made with the transversely modulated beam and x-z EEX

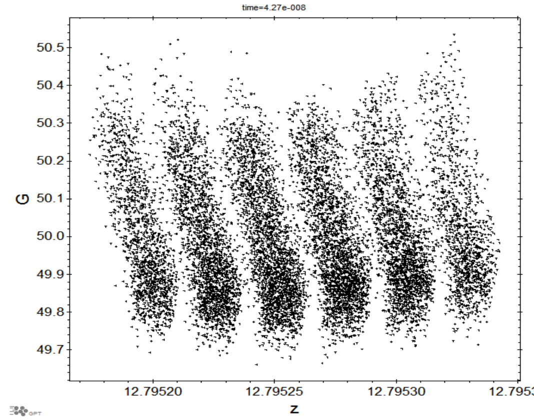

Figure 5: Micro-bunch structure after correction for the energy modulation. Energy spread is increased by the deceleration to 0.4% in RMS.

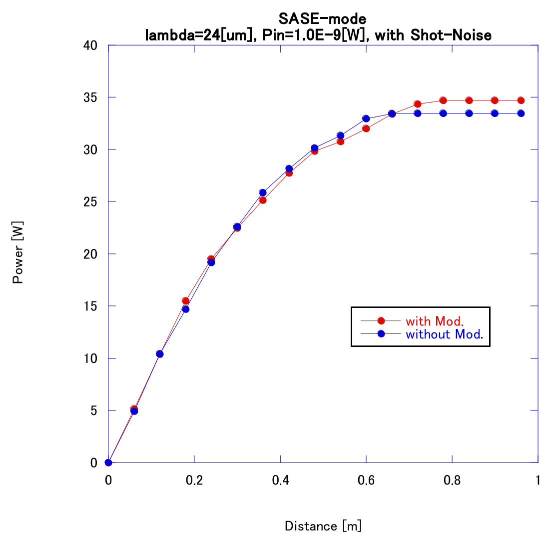

Figure 6: FEL gain curve as a function of the undulator length.

was studied. Unfortunately, any significant enhancement on FEL gain was not observed, but a clear micro-bunch structure is successfully generated with this EEX technique as expected. We continue this study towards high gain FEL with the micro-bunch technique and investigate other applications.

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