FEL ENHANCEMENT BY MICROBUNCH STRUCTURE MADE WITH PHASE SPACE ROTATION

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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 and quality have 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 mechanical slits, is properly transformed into the density modulation in the longitudinal direction by the phase-space rotation. 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. For FEL, energy chirp made by the emittance exchange should be properly corrected. Simulation results and possible applications are discussed.

INTRODUCTION

Laser light is currently widely used for not only to reveal the nature dynamics, but also various applications. Advantages of the laser light over ordinal light source are short duration and coherence. As nature of the laser light, it is almost fully coherent not only in spatial, but also in temporal. In the state of the art technology of the laser, a very short pulse in range of ps to fs is easily obtained by employing mode-lock technique. In various process observed in nature, e.g. electron, nuclear, atomic, and molecular dynamics are in the same range, i.e. from ps to fs. By using these coherence and the short duration, the laser light can be a powerful tool to study these objects. On the other hand, the available energy (wavelength) range by the laser is limited from IR to near-UV. There is a strong demand for tunable, coherent, and short pulse light source. Free Electron Laser (FEL) is one of the solution providing such light. FEL is firstly proposed by J. Madey and now several FEL in X-ray region are in operation[2][3] and construction[4]. SASE FEL is grown from a shot noise and therefore has a large fluctuation, less temporal coherence, and broaden specturm. Seeded FEL as HGHG[5], EEHG[6], etc. which introduce small power laser light to initiate the radiation process have been proposed to improve the FEL performance. More direct density modulation in the bunch intensity is possible by employing the phase-space rotation technique.

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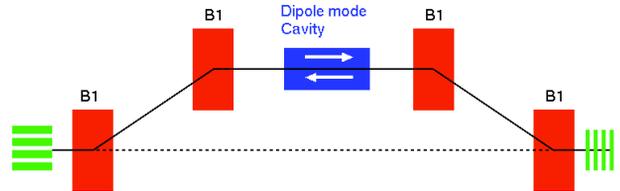
Figure 1: This is a schematic drawing of the beam line for x-z phase-space rotation which consists of one chicane and one dipole mode cavity. It converts the transversely modulated beam to the longitudinally modulated beam.

The schematic view of the beam-line to make the micro-bunch structure by the phase-space rotation is shown in Fig. 1. The beam-line consists from one chicane and one dipole mode RF cavity, such as TM_{110}. The transversely modulated beam generated by mechanical slits is converted to the longitudinally modulated beam. In general, temporal modulation such as micro-bunching can be produced by a photo-cathode with a temporal laser intensity modulation, or laser-beam interaction in undulator like the seeded FEL. It requires a state of the art of technology. On the other hand, the transverse spatial modulation can be made with the mechanical slits and ordinal beam optical components. It is therefore easily obtained. The x-z phase-space rotation give another way to produce the micro-bunching which is applicable for the seeded FEL.

The matrix representation of the beam line M_{EEX} (EEX section) is expressed as

$$M_{EEX} = M_D(\eta, \xi, L) M_C M_D(\eta, \xi, L)$$

$$= \begin{bmatrix} 0 & 0 & -L/\eta & \eta - L\xi/\eta \\ 0 & 0 & -1/\eta & -\xi/\eta \\ -\xi/\eta & \eta - L\xi/\eta & 0 & 0 \\ -1/\eta & \dfrac{-L}{\eta} & 0 & 0 \end{bmatrix} \quad (1),$$

where M_D and M_C are matrices for the dog-leg and the cavity, h is dispersion, x is momentum compaction, and L is the section length. The matrix is defined in x and z phase-space which is four dimensional in total. Here, the matching condition of the cavity strength parameter k and h given as

$$1 + \eta k = 0 \quad (2),$$

is assumed where k is defined as

$$k = \frac{V_0}{aE_0} \qquad (3),$$

where V_0 is RF acceleration at $x=a$, and E_0 is the beam energy. Because the cavity is a dipole mode, the acceleration depends on the transverse position x and there is no acceleration at all in the center, $x=0$. As clearly shown in Eq. 1, M_{EEX} has no diagonal components and x and z phase-space distributions before the section are transferred to z and x phase-space after the section, respectively. If the beam is transversely modulated at the entrance, the modulation is transffered to the longitudinal modulation, i.e. temporal modulation or micro-bunching. This is a brief explaination of the micro-bunch formation with the phase-space rotation.

SIMULATION

To demonstrate the FEL enhancement with the micro-bunch structure with the phase-space rotation technique, we performed a simulation. The simulation was made with GPT particle tracking code[8] for the micro-bunching formation part and followed by GENESIS for the FEL process. Table 1 shows the parameters in the simulation. In the simulation, a electron bunch with 25 MeV energy, 1.0nC charge , 2.0 p mm.mrad normalized emittance, and 2mm diameter is set. The bunch intensity is uniform like a beer-can shape.
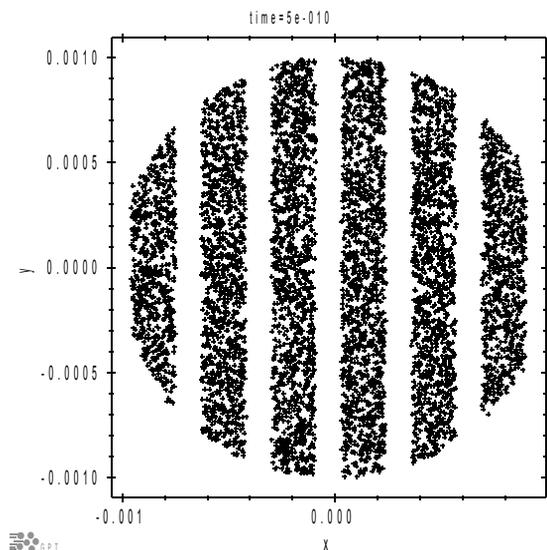
Figure 2: Particle distribution after the beam clipping by the mechanical slits in x and y plane is shown.

Figure 2 shows the particle distribution after the beam clipping by the mechanical slits in x and y plane. The round beam is clipped periodically in x direction. The slit width is 200mm and the interval is 330 mm.

Figure 3 shows the particle distribution at the exit of the EEX section. The micro-bunch structure in z direction is clearly observed in the distribution. The z-g correlation is also recognized. It is caused by (1,3) and (1,4)

components in Eq. 1 which gives the correlation through x before the EEX section. The energy spread is 3.2 % in full-width which is dominated by this correlation and it is obviously too much for FEL process.
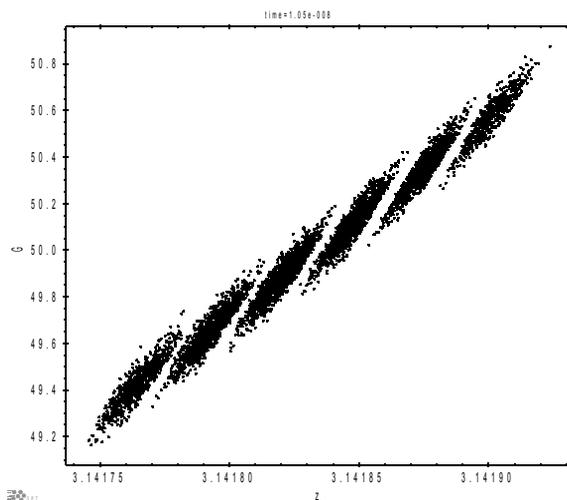
Figure 3: An example of particle distribution after EEX section in z (horizontal axis) and g (vertical axis) plane.

Table 1: Parameters for the Simulation

Parameter	Value	Unit
Bunch charge	1	nC
X Emittance	2	p mm.mrad
Beam energy	25	MeV
Slit width	200	mm
Slit interval	330	mm
V_0/a	1.69	MV/m
h	62.7	mm

To remove the correlation, another TM$_{010}$ normal mode cavity is placed after the EEX section and the bunch is placed at the zero-cross where the bunch head is decelerated and the bunch tail is accelerated. Fig. 4 shows the z-g distribution after TM$_{010}$ mode cavity. The strong correlation is now removed. The beam is then sent to the undulator section. The undulator parameter K is 1.08 and the period is 60mm. To maintain the beam size in the undulator section, Q-triplet was placed. At the entrance of the undulator section, the total bunch charge was 0.6nC, the average beam energy was 25.3 MeV, and the relative energy spread was 0.1% in rms. The period of the micro-bunch structure was 26 mm.

The undulator 1st harmonic wavelength is 26mm which is matched to the micro-bunch period and a rapid growth of the FEL power by a coherent radiation is expected. The power evolution along the beam line was obtained with GENESIS code as shown in Fig. 5. As a reference,
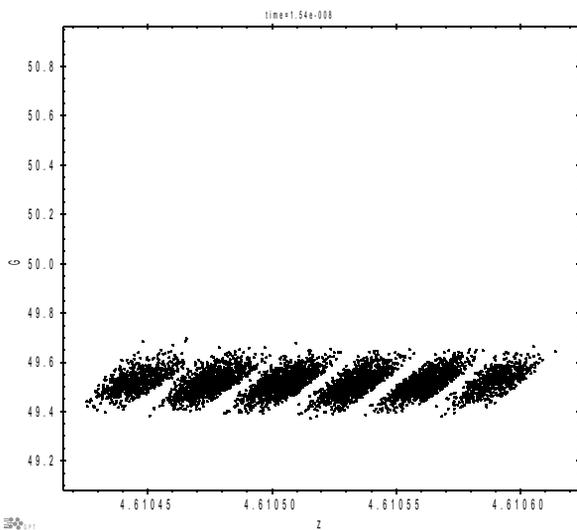
Figure 4: Particle distribution after TM_{010} mode cavity in z (horizontal axis) and g (vertical axis) plane. The strong correlation was removed giving 0.1% energy spread.

we perform another simulation with the same conditions, but no slits. In Fig. 5, the red solid line shows the FEL power with slits and the blue solid line shows that without slits. Comparing these curves, some enhancement is recognized by the micro-bunching. The bunch charge with slits is 0.6 nC, i.e. 40% less that without slits case. By considering the bunch intensity, the enhancement is larger than that shown in Fig. 5, but it is not great.
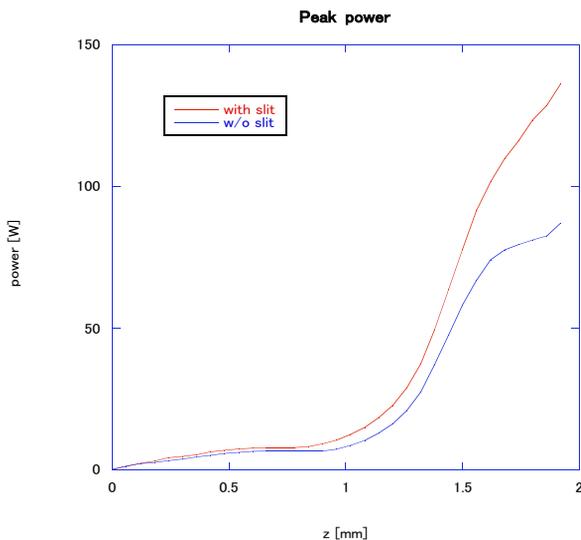
Figure 5: The power evolution of FEL with slits (red line) and without slits (blue line) are shown. Some enhancement by the micro-bunch is recognized.

The power spectrum is shown in Fig. 5. Data are shown with the same manner as that in Fig. 5, i.e.the red line shows that with slits and the blue line shows that without slits. In addition to the first harmonic, 26 mm, another

peak at 20 mm was recognized. This peak is not understood well.
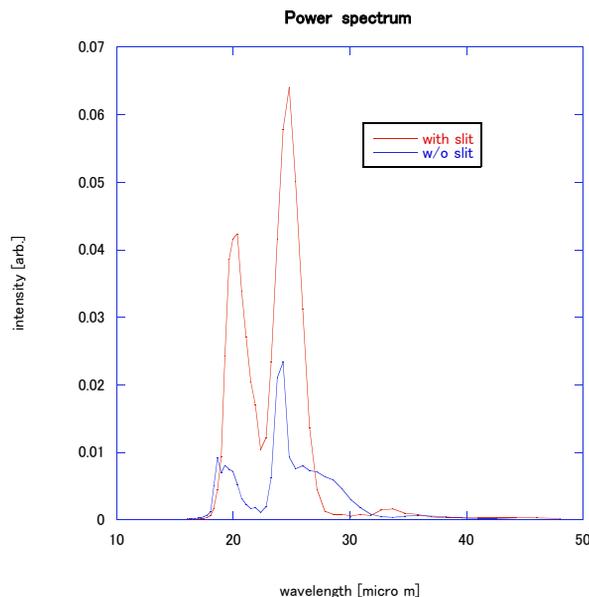
Figure 6: The power spectrum of FEL radiation with and without modulation by slits. In addition to the first harmonic, 26 mm, another peak at 20 mm was recognized.

CONCLUSION

A x-z exchange is studied based on the phase-space rotation technique. The complete x-z phase-space exchange was confirmed by a simulation. The spatial modulation in x direction made with mechanical slits is transferred to the longitudinal space resulting the micro-bunch structure. A strong correlation caused by the emittance exchange, can be removed by a TM_{010} cavity. FEL radiation with this micro-bunched beam was examined and some enhancement was observed by comparing to the beam without the micro-bunching.

ACKNOWLEDGEMENT

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