FOCAL POINT LASER-FIELD AS OPTICAL SEEDER

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Abstract

Focusing laser beam in wavelength size, passing electron beam at focal point in normal direction to the laser axis, we may apply periodic velocity modulation on the electron beam at optical wavelength. With energy chirp, the electron bunch is longitudinally compressed in the magnetic chicane. With appropriate depth of optical modulation and energy chirp, we may obtain micro-bunching at compressed wavelength after the chicane. If the slice energy spread of incoming electron beam is very low, we may compress the optical modulation down to X-ray wavelength, in principle. For example, using 2nd harmonic YAG-laser at 532 nm (green), the resulting optical modulation becomes 266 nm, then compressing bunch length by 1/60 and 1/30 in two stage bunch compressors, we may obtain 1 Å. The energy chirp will be compensated due to single bunch wake field in the linear accelerator. Sending the beam into undulator line, the density modulation will provide seeding, which will be strongly amplified and create single longitudinal mode with full coherence. If we use femto-second laser, such as TiSa in the optical modulator, we can obtain atto-second pulse of X-ray after the compression.

MOTIVATION

SASE-FEL: Self-amplified Spontaneous Emission Free Electron Laser, as it was named the spontaneous radiation (noise power) is amplified along with long undulator line, and reaches to saturation level. Since its power level is extremely higher than conventional X-ray sources, even higher than 3rd generation light sources, many new scientific applications are expected. Also the short pulse feature in femto-sec range is expected to be an important feature for analysing fast chemical and physical properties of condensed matter.

However, since SASE-FEL process starts from the spontaneous radiation at upstream undulator, the resulting saturated radiation power varies by shot-to-shot. And most importantly, there are many longitudinal modes, same as ruby laser does, temporal profile has many spikes, thus longitudinal coherence is quite limited.

If we seed a coherent signal from upstream undulator, whose power level has to be higher than spontaneous radiation, only the seeding signal will be amplified and saturated, thus it becomes (1) fully coherent, (2) temporally single-mode, and (3) stable energy in pulse-to-pulse. These features are favourable to all kind of scientific applications. Therefore, various proposals have been made on seeding schemes, including HGHG, HHG and wavelength shift [1, 2, 3]. They are promising approach to generate coherent radiation at VUV and also X-ray region. All of them use non-linear higher harmonic generation in high gain FEL, which requests high density electron beam.

In this paper, the author will propose a new approach: seeding density modulation at optical wavelength using conventional laser, and compress the bunch length together with wavelength of optical modulation down to X-ray wavelength. It does not rely on higher harmonic generation. Operational principle is simple. But there are many technical difficulties. However, the author believes that with extensive R&D efforts, in near future using this scheme we will be able to reach the X-ray wavelength with clean seeding signal after compressing bunch by factor of 1000 times. What we do is writing wave or coding signal on the electron beam, and transfer to the X-ray world.

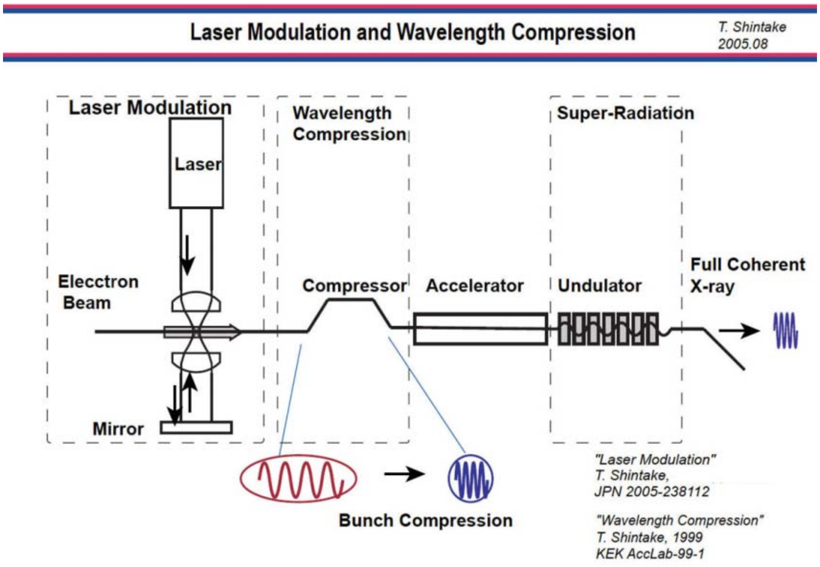

Fig. 1 Laser optical modulation and wavelength compression. Energy chirp after the compressor can be corrected by single bunch wake field and off crest acceleration in the linear accelerator.

BASIC CONFIGURATION

Figure 1 shows the basic configuration of this seeding scheme. We apply energy chirp on the incoming electron bunch, and add energy modulation at optical wavelength in the laser modulator, then compress the bunch length in the magnetic chicane. At the same time the velocity modulation is converted into density modulation at compressed short wavelength. The compression factors for the bunch length and the modulation wavelength are exactly same. After accelerating the beam up to higher energy, and sending into undulator, the bunch will radiate coherent signal. If the

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wavelength of undulator radiation meets with the density modulation on the bunch, the undulator will radiate coherent radiation at super radiant mode.

In case of SASE-FEL of X-ray wavelength, we need 1/1000 times compression. Any kind of non-linear effect in magnetic chicane or wake-field will smear the optical modulation. However, if the residual density modulation exceeds the Schottky noise level, which is usually a few kW level only, the density modulation will provide coherent seeding signal to the SAS-FEL.

Similar approach was discussed independently by T. Shaftan and experimentally demonstrated using DUV FEL at BNL [3], where the tuning range that can be achieved is full range through a 10% tuning around each harmonic and switching between different harmonics.

APPLYING LASER MODULATION ON THE CATHODE

We may apply laser field directly on the cathode and create modulation on electron beam. If the electric field intensity of the laser field is strong enough, the accelerating field initially applied on the electron gun will be controlled, thus the current flow can be switch ON-OFF at the speed of the optical frequency. However, the thermal motion of electron erases the modulation at optical wavelength during acceleration as discussed below.

Fig. 2 shows electron trajectory in a constant accelerating field of E. The kinetic energy increases along its trajectory as

$$W_k(z) = eE_z \cdot z + W_{th} \tag{1}$$

Where W_{th} is the initial kinetic energy on the cathode, which is given by the thermal energy,

$$\left\langle \frac{1}{2} m_e v_z^2 \right\rangle = \frac{1}{2} kT \tag{2}$$

Solving eq. (1) under initial condition of eq. (2), we can compute thermal effect on the trajectory. Here we graphically estimate the thermal effect, refer Fig. 2. An electron starts from the cathode with zero initial energy, which follows curved line **A**, and reaches to the final position z_f at time t_f, where the velocity is very close to the speed of light. If the electron starts from the cathode with finite initial velocity, it follows trajectory **B**, at time t_f it runs more Δz, which smears out the modulation. This effect can be graphically estimated as follows. In the trajectory **A**, near the cathode, electron reaches to the point (t_1, z_1) where the kinetic energy becomes equal to the initial energy of trajectory **B**:

$$ct_1 = \frac{m_0 c^2}{eE_z} \sqrt{\frac{2W_i}{m_0 c^2}}, \quad z_1 = \frac{W_i}{E_z}, \tag{3}$$

Trajectory **B** is exactly same as **A** if we shift the point (t_1, z_1) to origin (0, 0). Assuming the final energy is relativistic, the distance Δz is given by

$$\Delta z = ct_1 - z_1 \tag{4}$$

As an example, we assume accelerating field of 10 MV/m, and thermionic cathode operating at 1800 K, thermal energy in z-direction is 74 meV, and we find:

$$\begin{aligned} t_1 &= 61 \text{ femto-sec.} \\ z_1 &= 7.4 \text{ nm} \\ ct_1 &= 19\ \mu\text{m} \\ \Delta z &= 19\ \mu\text{m} \end{aligned} \tag{5}$$

Δz is much longer than the optical wavelength, thus the modulation will be totally smeared out.

In case of RF-gun, the cathode temperature is room temperature, and cathode field is much higher, thus thermal diffusion becomes smaller. Assuming a very high acceleration field such as 100 MV/m, the diffusion distance becomes $\Delta z = 1.1\ \mu\text{m}$. They are summarized in Table 1. If we use CO_2 laser at 10 μm wavelength, the modulation will remain. Tuneable infrared radiation from OPO (Optical Parametric Oscillator) will also be a candidate.

Table 1: Thermal diffusion effect for electrons starting from the cathode

Physical Parameter	Thermionic Gun	Photo-cathode rf-gun
Field Gradient: E	10 (MV/m)	100 (MV/m)
Temperature: T	1800 (K)	300 (K)
Thermal energy: W_{th}	74 (meV)	12 (meV)
Equivalent point: t_1 z_1 ct_1	61 fs 7.4 nm 19 μm	3.8 fs 0.12 nm 1.1 μm
Diffusion length: Δz	19 μm	1.1 μm

In case of the photo-cathode rf-gun, the laser beam is introduced on the cathode from normal direction, and the electric field of the laser is oriented paralleled to the cathode surface, which takes minimum on the cathode

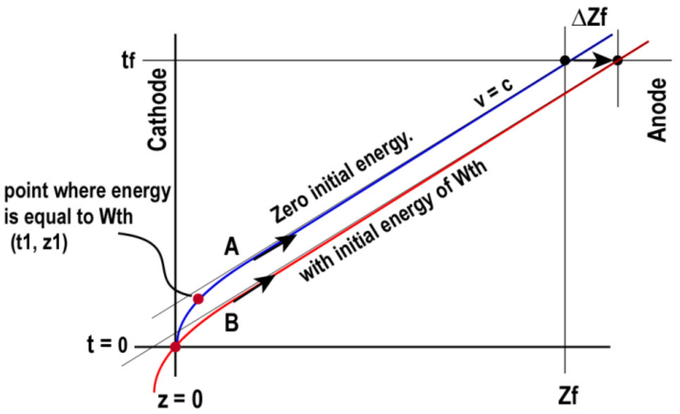

Fig. 2 The electron trajectory in the constant acceleration field. Starting from the cathode (z = 0), reaches to final position z_f at the time of t_f. With initial energy, the electron runs more: Δz, which smears out the modulation.

because the cathode is electric conductor, thus the laser field does not directly modulate velocity of emitting electron. However, in case of pulsed laser, if it is not seeded with coherent beam there are multi-modes in longitudinal direction, resulting in temporal variation. If the period of this variation is longer than ΔZ, the produced electron bunch from the rf-gun will contain density modulation. This will be a possible source of CSR instability in the magnetic chicane. Tiny density fluctuation on electron beam is amplified due to negative slope of energy (energy loss at bunch head, opposite to the wake-fields), which is amplified through dispersion in the bunch compressor, results in higher CSR radiation and positively feedbacks to the energy modulation on the electron bunch, cause CSR instability.

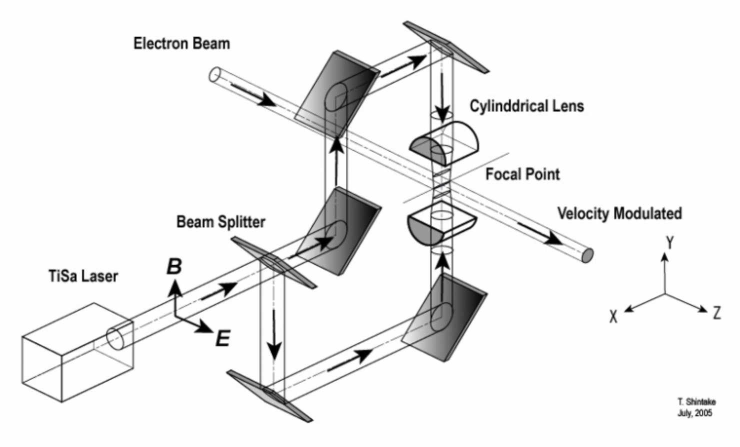

Fig. 3 Laser modulation, using focal point field in the standing wave of the laser beam. To make interaction area wider, the cylindrical lens is employed rather than spherical lens. Polarization is chosen as to make the electric field being oriented to the electron path.

THRESHOLD ENERGY

Reason why such a small thermal energy causes diffusion on accelerating electron in high gradient is that the electron remains near the cathode when the speed is not high enough. It can be shown by the following equations.

$$v=\sqrt{\frac{2eE_z}{m_0}\cdot z} \qquad (6)$$

$$dt=\frac{1}{v}dz \propto \frac{1}{\sqrt{z}}\cdot dz \qquad (7)$$

Near the cathode, z is small, thus it takes long time to travel. Once the electron departs from the cathode and increases speed, the travelling time for unit distance becomes shorter, and it becomes independent from initial thermal energy.

The diffusion distance during acceleration between point-1 and point-2 is given by

$$\begin{aligned}\Delta z_{th}&=\frac{\Delta\gamma_{th}}{\gamma'}\left(\frac{1}{\beta_1}-\frac{1}{\beta_2}\right)\\ \gamma'&=eE_z/m_0c^2 \qquad (8)\\ \Delta\gamma_{th}&=kT/2m_0c^2\end{aligned}$$

For example, to accelerate beam up to 8 GeV (β_2 = 1) on 20 MV/m field gradient (γ' = 39.1/m), assuming thermionic gun (74 meV, $\Delta\gamma_{th}$ = 1.4 x 10^{-7}), to make the diffusion distance being lower than quarter wavelength of 4th harmonic of YAG: ΔZ<60 nm, we fined

$$\frac{1}{\beta_1}-1>16.7 \qquad (9)$$

Thus, β_1 > 0.056, or the beam energy has to be higher than 810 eV. If we apply the laser modulation at this energy or at higher energy, the modulation will be kept up to relativistic energy.

At high energy, eq. (8) becomes

$$\Delta z_{th}=\frac{\Delta\gamma_{th}}{\gamma'}\cdot\frac{1}{2\gamma_1^2}\left[1-\left(\frac{\gamma_1}{\gamma_2}\right)^2\right]. \qquad (10)$$

For example, if we compress the bunch into 1 Å at 1 GeV and accelerate to 10 GeV with 30 MV/m accelerating gradient, the diffusion due to thermal energy becomes ΔZ = 0.3 femto-meter, this is much smaller than 1 Å, thus the modulation will be kept.

The betatron oscillation of each electron inside the bunch causes path difference and smearing effect. Average path difference can be estimated by

$$\Delta z_\beta=\frac{2\varepsilon_n}{\pi^2\gamma}\cdot\frac{L}{\langle\beta\rangle} \qquad (11),$$

Assuming, $\varepsilon_n=1\times10^{-6}\pi mm\cdot mrad$, L = 300m, β = 30 m, the path difference becomes 2 Å. Therefore, simple betatron oscillation contributes to erase micro bunching. But inside the bunch, near the core, betatron oscillation amplitude is lower, thus the modulation pattern will remain. This is ideal case, there is only accelerating static field, and no magnetic component which will create dispersion and cause path length difference inside the bunch and will smear the modulation patter. Further careful study is required.

LASER MODULATION

When an electron beam passes through a laser beam in free space, usually there is no energy transfer with relativistic electron beam. This is because the laser field is transverse electro-magnetic field, and no longitudinal electric field exists. “The laser acceleration” technology uses dispersive media, such as gas or plasma, to obtain longitudinal electric field propagating with speed of electron.

When we pass an electron in an undulator, the electron transversely oscillates. We inject laser beam from behind of the electron, where longitudinal drift velocity of electron is slower than speed of light even in relativistic case due to transverse velocity component, and the electron delays from laser beam. With optimum tuning condition, for each one period of undulation, the electron delays one wavelength on laser field, thus recover phase and continue to exchange energy through $v_t \cdot E_t$ coupling.

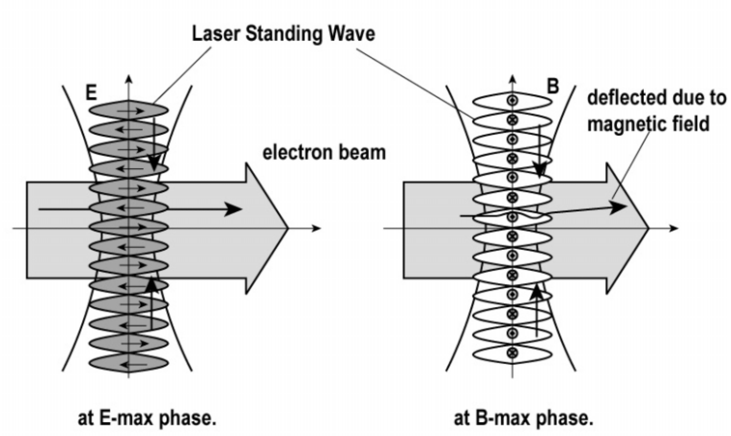

Fig. 4 Overlapping two laser beams create standing wave. At the electric field maximum location, electron receives velocity modulation. In between these maximums, the magnetic field deflects beam, which deteriorate beam emittance, also cause Compton scattering with laser photon and generate gamma-ray, which contributes to energy spread.

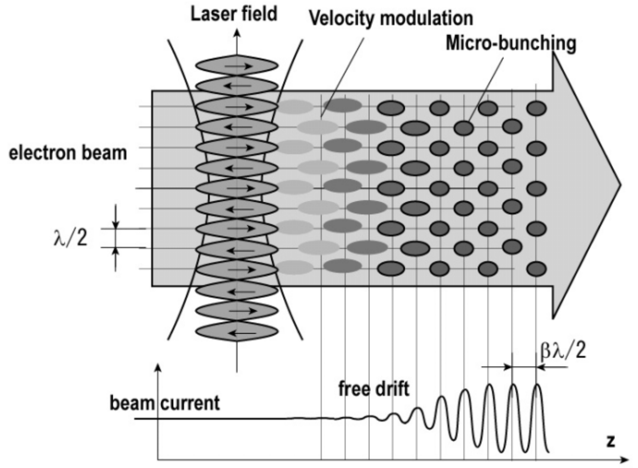

Fig. 5 Standing wave laser beam adopts velocity modulation and generate density modulation pattern at double frequency.

This type of laser modulator is so called “inverse FEL”, and experimentally demonstrated elsewhere. However the system becomes complicated.

Here we introduce new scheme, which uses transverse electric field at focal point as illustrated in Fig. 3. This scheme uses same configuration as the spot size monitor tested at FFTB SLAC [4], but in this case we utilize the electric field. Since two leaser beam overlap at the focal point, the standing wave is created. By choosing polarization of the laser beam as the electric field being oriented to the electron beam path at the focal point, the electron beam receives energy modulation through $v_z \cdot E_z$ coupling at each electric field maximum points with $\lambda/2$ apart as Fig.4 left. In between them, there are magnetic field maximum points, where electron receives transverse kick from the magnetic field as shown in Fig. 4 right. This transverse coupling provides Compton scattering of laser photon, which causes increase of energy spread.

If the spot depth is much larger than laser wavelength, $v_z \cdot E_z$ oscillates along its trajectory and integration becomes zero, thus the electron does not receive energy gain. If we focus the laser beam into very small spot, the integral becomes non zero.

Here we assume Gaussian laser beam, and focus into a long elliptical spot using cylindrical lens as shown in Fig. 3. Here we define the coupling coefficient as follows.

$$T = \frac{\int_{-\infty}^{+\infty} E_z(z, t = z/c) \cdot dz}{\int_{-\infty}^{+\infty} E_z(z, t = 0) \cdot dz} = \mathrm{e}^{-(k\sigma_z)^2/4}. \qquad (12)$$

Function T is plotted in Fig. 6. To obtain substantial coupling, we need to focus the laser spot very small close to the laser wavelength. From Fig. 6 we find that in order to obtain coupling of 0.1 or higher we have to focus the spot size $\sigma_z < 0.5\lambda$.

Can we focus the laser into such a small spot? The answer is yes. The CD player uses photo-pickup, where a short focal lens is used to focus laser beam into small spot in wavelength dimension to fit with the micron-size pits, and read out the reflection from those. The relation between the lens aperture, focal length and minimum spot size is given by

$$\sigma_z = \frac{\lambda}{\pi\theta}$$
$$NA = n \cdot \sin\theta \qquad (13),$$
$$F = \frac{f}{D} \approx \frac{1}{2NA}$$

Where *NA* is called “Numerical Aperture” and higher *NA* provides smaller spot size, but it technically limited less than 1. One of the most advanced lens system is employed in the lithography system in Si-process, for example, NA of 0.85 has been realized in 157 nm F_2-laser lithography and 70-nm line width has been achieved[5].

From eq. (13), in order to obtain $\sigma_z < 0.5\lambda$, we need $\theta = 2/\pi = 0.64$, and NA = 0.59. There are commercially available products of cylindrical lenses having NA value 0.5 or even higher.

Using pulsed laser of 2nd harmonic of YAG-laser at 532 nm, assuming 1 mJ pulse and 10 nsec duration, this is small class laser oscillator in commercial production line, we may obtain 170 MV/m of peak electric field at the focal point, and 16 eV of modulation energy. This is quite enough for our purpose.

Table-2: Example laser system and modulation energy.

YAG-Laser 2nd			
wavelength	λ	532	nm
Output power	100 kW, 10 nsec, 1 mJ		
Focusing	Cylindrical lens		
Focusing length	*f*	5	mm
Numerical aperture	*NA*	0.6	
Matched laser beam size	$\sigma \sim 0.5D$	3	mm
Focused spot size	σ_{z0}	266	nm
Transverse width	σ_{x0}	3	mm
Field intensity	E_{z0}	170	MV/m
Modulation period	λ_{mod}	266	nm
Coupling Constant	*T*	0.1	
Modulation Energy		16	eV

REQUIRED ENERGY CHIRP AND OPTIMUM MODULATION

In the magnetic chicane, the bunch length is compressed according to its initial energy chirp: bunch head is lower energy and higher at tail, so that head part delays and tail catches up, results in compressing bunch length. If the optical modulation system is located upstream of the bunch compressor, the energy modulation will overlap with the linear energy chirp. After bunching, the energy modulation will be converted into density modulation with shorter wavelength. If the energy modulation is too strong, the micro bunching will be over compressed and modulation contrast becomes lower. Thus there is certain relation between linear energy chirp and micro energy modulation. As shown in Fig. 8 left, there are three energy components: the initial energy chirp, optical modulation and energy spread:

$$E = E_0 - V_{I.RF} \cdot k_{RF} z - V_{\text{mod}} \sin(2\pi z/\lambda_{\text{mod}}) + \sigma_e, \qquad (13)$$

Where $V_{I.RF}$, k_{RF} is the RF cavity voltage to produce energy chirp (off crest component), V_{mod} is the optical modulation voltage, λ_{mod} is modulation wavelength before compression and σ_e is the energy spread. In the chicane, the bunch length is compressed according to $z_f = z_i + R_{56}\delta_i$. Optimum bunching condition is illustrated in Fig. 8 right, where the longitudinal spread of bunched beam becomes minimum, which is given by the following condition. Note the no space charge effect is considered in this discussion.

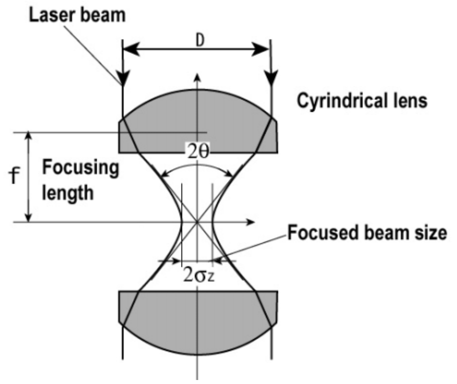

Fig. 7 High-NA focusing optics.

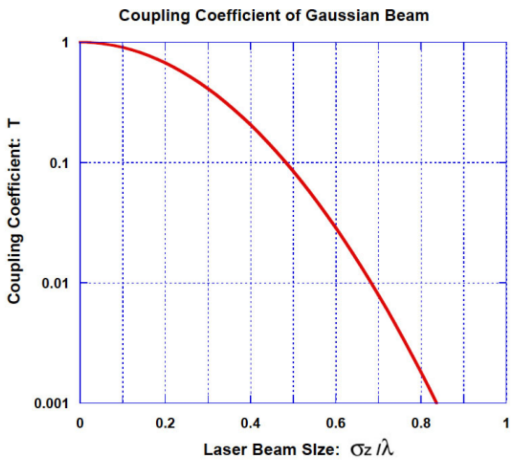

Fig. 6. Coupling coefficient as a function of the laser beam spot size.

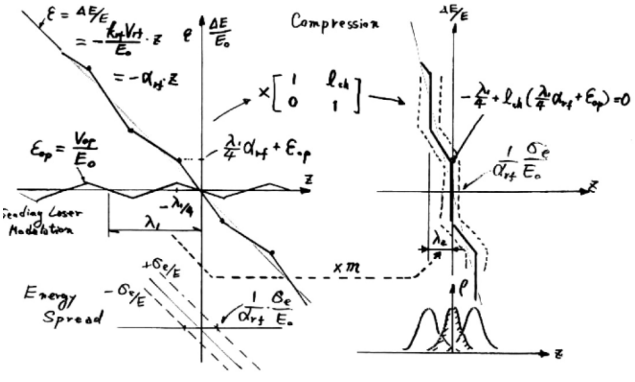

Fig. 8. Phase diagram of electron bunch before and after the compression.

$$\left.\frac{\partial z_2}{\partial \delta_2}\right|_{z=0} = 0, \tag{14}$$

$$\frac{V_{I.RF}}{E_0} k_{RF} + \frac{V_{\mathrm{mod}}}{E_0} k_{\mathrm{mod}} = R_{56}{}^{-1}, \tag{15}$$

The bunch compression factor is

$$m = \sigma_{zf} / \sigma_{zi} = 1 - \frac{V_{I.RF}}{E_0} k_{RF} R_{56} \tag{16}$$

At high compression ratio, i.e., we can approximate

$$\frac{V_{I.RF}}{E_0} = \left(k_{RF} R_{56}\right)^{-1} \tag{17}$$

For the optical modulation the optimum condition is,

$$\frac{V_{\mathrm{mod}}}{E_0} = m \cdot \left(k_{\mathrm{mod}} R_{56}\right)^{-1}. \tag{18}$$

For example, if we compress bunch length by 1000 times at 3 GeV, m = 0.001, with R_{56} = 40 mm, and λ_{mod} = 266 nm, the required modulation becomes $V_{\mathrm{mod}} = 1 \times 10^{-9} E_0$, that is optical velocity modulation becomes 3 eV. This value will be easily provided by the laser modulation as shown in Table 2.

If the energy spread is large, the modulation pattern will be smeared out. The energy spread has to be smaller than modulation energy. If the electron energy spread is still as low as the thermal energy: 74 meV, the modulation will be kept through the bunch compression process. The wavelength of the micro-bunching after the compressor becomes $\lambda = m \cdot \lambda_{\mathrm{mod}}$. If we use 532 nm wavelength, the modulation period becomes 266 nm, then, after the compression with m = 0.001, the modulation wavelength becomes 0.27 nm.

If we use femot-second laser, such as TiSa to optical modulator, we will be able to obtain atto-second pulse of X-ray after the compression.

CONCLUSIONS

New optical modulation scheme has been proposed in this paper. If we apply velocity modulation at optical wavelength, and compress it with bunch length, we will have density modulation at X-ray wavelength range. At least in an ideal case, mathematics shows possible parameter set. If we assume 1000 times compression ratio, we will have direct seeding source at X-ray wavelength.

Further studies will be required on non-linear field in bunch compressor, non uniform velocity distribution in bunch, energy spread due to radiation excitation, etc.

In year of 2007, we will install a laser modulator in our test accelerator to demonstrate velocity modulation, and compress the wavelength by ten times in bunch compression to seed FEL at 50 nm range.

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