WIDE BAND SEEDING AND WAVELENGTH COMPRESSION

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Abstract

The "wavelength compression" has a potentiality to generate seeding signal at the nano-meter wavelength by squeezing optical wavelength of the visible laser beam on a high energy electron beam. Applying energy chirp on the incoming electron beam and overlapping laser beam to produce micro-period energy modulation at optical wavelength, the velocity modulation can be converted into density modulation at shorter wavelength during the bunch compression in a chicane. Using 255 nm 4th harmonic YAG laser as modulation signal, and if we compress bunch length 20 times, we can generate coherent signal below 10 nm. By cascading multiple bunch compressors, higher compression ratio will be obtained. To go X-ray wavelength, we may use HGHG scheme after the wavelength compression. Since compression factor is variable, it becomes tuneable coherent source at X-ray wavelength, which is suitable to seeding the X-ray FELs.

Using femto-second laser at the modulator, it will generate atto-second pulse at short wavelength.

MOTIVATION

SASE-FEL: Self-amplified Spontaneous Emission Free Electron Laser, as it is named, the spontaneous radiation (noise power) is amplified in the long undulator line. If the undulator is long enough, power level reaches to saturation. 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 with using this source. Also the short pulse feature in femto-sec range is expected to be an important feature for analysing fast chemical and physical reaction of condensed matter.

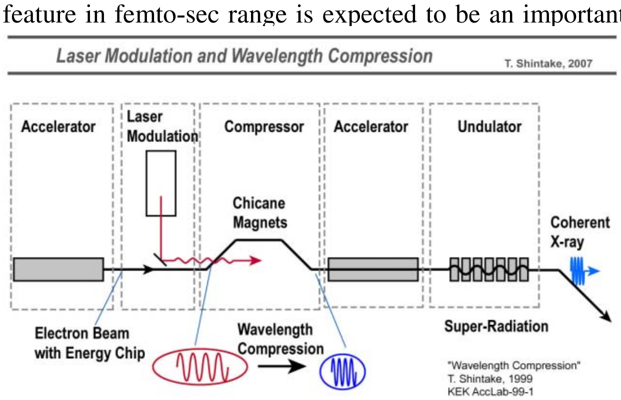

Figure 1: Laser optical modulation and wavelength compression. Applying both the energy chirp at rf wavelength and micro-period energy modulation at optical wavelength using laser beam, the modulation pattern can be compressed into short wavelength during bunch compression, which provides seeding signal to the downstream undulator. By combining with HGHG scheme in the downstream undulator line, an X-ray seeded FEL will be realized.

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

If we seed a coherent signal from upstream undulator, the seeding signal will be amplified and saturated. It becomes (1) fully coherent, (2) temporally single-mode, (3) stable energy in pulse-to-pulse and (4) power level controllable. These features are favourable to all kind of scientific applications. Therefore, various proposals have been made on seeding schemes, including HGHG, TUHG,[3,4,5]. G. Lambert reported first observation of amplification of seeded FEL using higher harmonic generation in gas [HHG] at 160 nm in SCSS test accelerator[7].

They are also promising approach to generate coherent radiation at nano-meter wavelength. However they are not wavelength tuneable. In actual machine, a small wavelength shift was observed experimentally at DUV FEL at BNL[6]. However the observed wavelength shift was as low as 1%.

For fully tuneable seeding, the wavelength compression scheme was originally proposed by the author in 1999[1]. As shown in Fig. 2, a modulator, a short undulator was assumed as energy modulator, where a laser beam was introduced from upstream[2]. The velocity modulation is created through $E_t \cdot v_t$ coupling in the undulator. After the undulator, the electron bunch is accelerated at off-crest phase to apply energy chirp, then the bunch length is compressed. After accelerating the beam, the modulated electron beam is fed into undulator to generate coherent radiation. This scheme requires many hardware components, and also spontaneous emission in the upstream undulator cause additional energy spread on the incoming electron beam.

In the previous paper[2], the author proposed a scheme to generate energy modulation at optical wavelength using the focal point laser field. However, the laser beam has to be focused into a very small spot, and the fraction of overlapping the laser beam to the electron beam is fairly small, as a result overall modulation efficiency becomes small.

To overcome this difficulty, the author proposes a new scheme which provides higher coupling efficiency.

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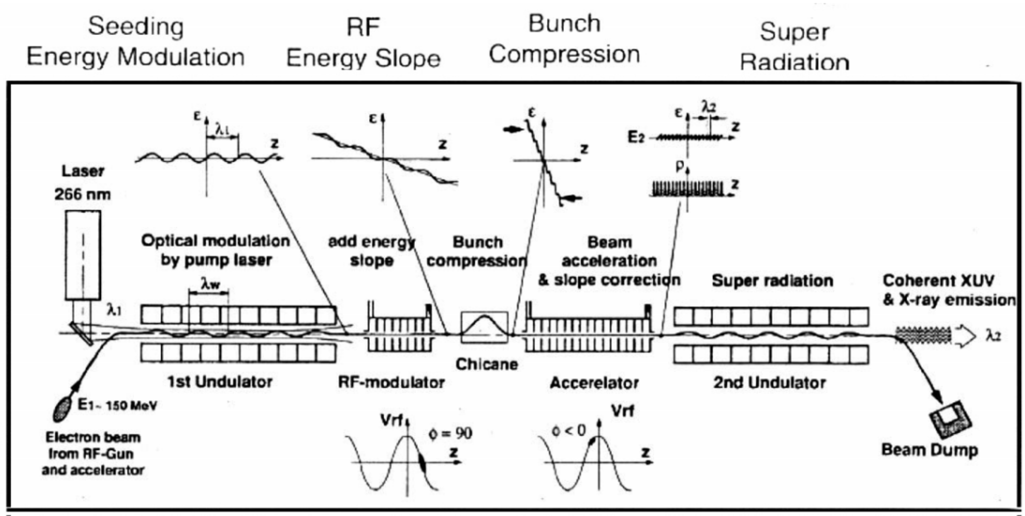

Figure 2: Original wavelength compression scheme[1], which uses independent undulator at upstream as the optical energy modulator, followed by short accelerator to adopt energy chirp. Dispersive section provides two functions of a bunch compression and energy-to-density conversion of optical modulation.

BASIC CONFIGURATION

Figure 1 shows the basic configuration of the new seeding scheme. We apply energy chirp on the incoming electron bunch in the upstream accelerator, and add energy modulation at optical wavelength at the entrance of the chicane, then compress the bunch length through the chicane. At the same time the velocity modulation can be converted into density modulation at short wavelength. The compression factors for the bunch length and the modulation wavelength are exactly same. After accelerating the beam to higher energy, and sending into undulator, the bunch will radiate coherent signal. If the wavelength of undulator radiation is tuned to the compressed modulation wavelength, the undulator will radiate coherent radiation at super radiant mode.

MODULATION PATTERN SMEARING

Electron beam has energy spread, which limits this seeding scheme. The longitudinal diffusion distance during acceleration between point-1 and point-2 is given by[2]

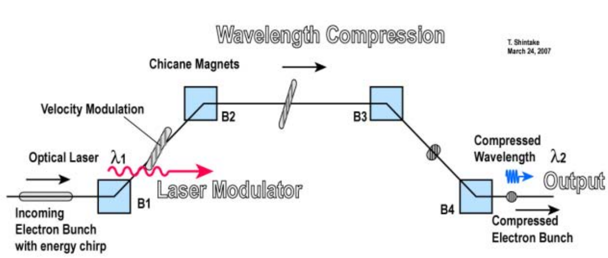

Figure 3: Overlapping laser beam and electron beam with oblique angle at the entrance of the magnetic chicane, the electron beam energy is modulated at optical wavelength. Since the incoming beam has energy chirp, the density modulation pattern is longitudinally compressed into short wavelength together with bunch length being compressed. By cascading multiple chicanes, we obtain high compression ratio, for example 1/10 x 1/10 = 1/100.

$$\Delta z = \frac{\Delta\gamma}{\gamma'}\left(\frac{1}{\beta_1}-\frac{1}{\beta_2}\right)$$

$$\gamma' = eE_z / m_0c^2 \quad , \quad (1)$$

$$\Delta\gamma = eV_{spread} / m_0c^2$$

For example, to accelerate beam up to 8 GeV (β_2 = 1) on 20 MV/m field gradient ($\gamma' = 39.1$), assuming the energy spread 30 eV, which is much higher than the thermionic energy (74 meV,), to make the diffusion distance being lower than 1 nm, we found the threshold energy 14 MeV. If we locate our laser modulator at beam energy higher 14 MeV, we may keep density modulation pattern at 1 nm.

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

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

Assuming, $\varepsilon_n = 1\times10^{-6}\pi mm\cdot mrad$, L = 300m, β = 30 m, the path difference becomes 2 Å. This is negligibly small for 1 nm modulation.

The space charge effect also contributes to smear out the density modulation. This effect can be estimated by the electron plasma frequency:

$$\omega_p = \gamma^{-3/2}\sqrt{\frac{e\rho_0}{m_e\varepsilon_0}} \qquad (3),$$

where ρ_0 is the electron density. For example, assuming beam current 100 A at 50 MeV, β-function 10 m, beam size 0.3 mm, the plasma frequency becomes 25 MHz. After travelling quarter plasma-wavelength, the density modulation becomes zero, i.e., after 3 m travel. It is known that the density modulation will recur again after quarter-wavelength. Within this length, we may accelerate beam to higher energy, where the plasma wavelength becomes longer, thus we may keep density modulation. If we locate modulator at 500 MeV, the quarter plasma wavelength becomes 100 m. This is long enough to maintain the density modulation.

CHICANE LASER MODULATIOR

Fig. 4 shows interaction of electron beam with laser field. Here we assume the laser beam has Gaussian distribution, its transverse size is w_0. The intensity and field distributions can be expressed as

$$I = I_0 e^{-2x^2/w_0^2}, \quad E = E_0 e^{-x^2/w_0^2} \qquad (4)$$

We consider one electron passing the laser beam with slope angle of α. The laser beam polarization is in the plane of the drawing. The energy gain of the electron during the passage is given by the following integration.

$$\Delta W = \int_{-\infty}^{\infty} \mathbf{E} \cdot d\mathbf{s} = \int_{-\infty}^{\infty} E_x \cdot dx = \int_{-\infty}^{\infty} E_0 \cdot e^{-x^2/w_0^2} \cos(\omega t - kz + \phi) dx, \qquad (5)$$

where ϕ is the phase of laser field. Assuming the electron velocity is close to light velocity, the phase term becomes

$$\omega t - kz = \left(\frac{\omega}{\beta c \cos\alpha} - k \right) \cdot z = \frac{kz}{2\gamma^2}(1+\gamma^2\alpha^2) = k'z, \qquad (6)$$

where k' is the synchronous wave number. It is corresponding to the wave number of undulator period, and $\gamma\alpha$ is the *K*-parameter.

$$k_s = \frac{k}{2\gamma^2}(1+\gamma^2\alpha^2), \quad \lambda_s = \lambda_0 \frac{2\gamma^2}{1+\gamma^2\alpha^2}, \qquad (7)$$

The energy gain becomes,

$$\Delta W = \sqrt{\pi}\, E_0 w_0 \cos\phi \cdot \exp\left\{ -\left(\frac{k_s l_0}{2} \right)^2 \right\}, \qquad (8)$$

Where l_0 is the interaction length of an electron to cross the laser beam: $l_0 = w_0/\alpha$. In order to obtain substantial modulation, the crossing length has to be smaller than the synchronous wavelength. From Eq. (8),

$$\frac{k_s l_0}{2} < 1, \quad l_0 < \frac{\lambda_s}{\pi}, \qquad (9)$$

In this condition the modulation energy becomes $\Delta W \sim E_0 w_0$. Using Eqs. (7) and (9), we find the condition for the laser waist size,

$$w_0 = \alpha l_0 < \frac{2\lambda_0}{\pi} \frac{\gamma^2\alpha}{1+\gamma^2\alpha^2} \qquad (10)$$

Due to the diffraction effect, the laser size expands along its path. If the electron trajectory stays within the laser field longer until the laser spot size becomes larger, the integral energy gain will cancel and become small. Therefore, the electron trajectory has to cross the laser beam with enough angles to make its interaction length smaller than the diffraction angle.

$$\alpha > \frac{\lambda_0}{w_0} \qquad (11)$$

Additionally the electron beam size has to be same size or smaller than the laser size

$$\sigma_0 \quad w_0 \qquad (12)$$

Table-1 summarizes those conditions for two cases. As seen in the table, for high energy, the required laser size becomes larger, thus easier to focus the laser beam, while it request smaller crossing angle. On the other hand, for lower beam energy, the crossing angle becomes large, but we need to focus laser beam into small size. In practical design of the bunch compressor, to obtain enough R_{56} parameter, the deflection angle becomes much larger than $1/\gamma$. In this case, $\alpha \gg 1/\gamma$, the synchronous wavelength and laser size and also the energy gain becomes non energy dependent function. Therefore this system has very wide energy bandwidth.

Table-1: Small and large angle cases.

Crossing Angle	Small Angle $\alpha = 1/\gamma$	Large Angle $\alpha \gg 1/\gamma$
Synchronous Wavelength	$\lambda_s = \gamma^2 \lambda_0$	$\lambda_s = 2\lambda_0/\alpha^2$
Required Laser Size	$w_0 < \frac{\gamma\lambda}{\pi}$	$w_0 < \frac{2\lambda}{\pi\alpha}$
Modulation Energy	$\Delta W = \sqrt{\pi}\, E_0 w_0$	$\Delta W = \sqrt{\pi}\, E_0 w_0$

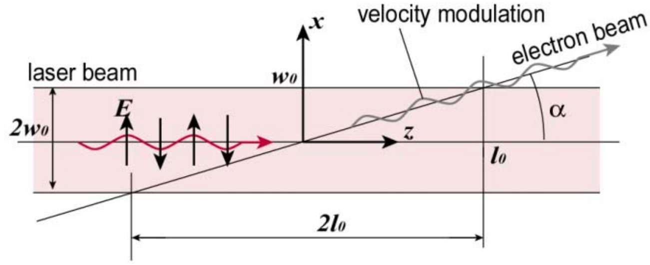

Figure 4: Electron beam passing through laser beam with oblique angle receives energy modulation.

REQUIRED ENERGY CHIRP AND OPTIMUM MODULATION

For the optical modulation the optimum condition is[2],

$$\frac{V_{\mathrm{mod}}}{E_0} = m \cdot \left(k_{\mathrm{mod}} R_{56} \right)^{-1}. \qquad (13)$$

Table-2: Example laser modulation system for two difference beam energy.

Target Wavelength	λ_2 (nm)	10
Compression Ratio	m	100:1
Laser Source	λ_1 (nm)	1060
Beam Energy	E (MeV)	50
	γ	100
Crossing Angle	α (mrad)	10
Synchronous Wavelength	λ_s (mm)	10
Interaction Length	L_i(mm)	3
Laser Spot Size	w_0 (μm)	32
Electron Beam Size	(μm)	100 β = 1 m
Laser Power	Watt	100
Field Intensity	E_0 (MV/m)	6
Energy Modulation	ΔW (eV)	200

At this condition, the compressed modulation has the maximum contrast. For example, if we compress bunch length by 100 times at 50 MeV, m = 0.01, with R_{56} = 10 mm, and λ_{mod} = 1064 nm, the required modulation becomes $V_{mod} = 10$ eV . This value can be easily provided by the laser modulation. However, if the energy spread is large, the modulation pattern will be totally smeared out. The energy spread has to be smaller than modulation energy.

There are experimental measurements on energy spread on electron beam from RF guns. Typically, energy spread right after the gun is about 10 keV or higher. This is much larger than the thermal energy spread. This is due to the space charge effect near by the cathode. In the case of the rf photo-cathode gun, the emitted electron beam from the cathode is already bunched, and its has high peak current value ~100 A. When the electron starts from the cathode, image charge on the cathode pulls the electron back and lowers the effective acceleration gradient. This effect varies along its radial position within the beam. Therefore, an electron emitted from the centre of the cathode and from the beam edge feels different field gradient, as a result, it cause energy spread.

On the other hand, in the case of the thermionic DC gun, all electrons gain the same energy, in principle. Only the self-potential gives energy difference, while it is fairly small. At 50 MeV, for 1 nC, 10 psec, the self-potential difference is 12 eV on the electron rest frame. We need further careful discussion on how this potential energy affects on particle motion on the laboratory frame.

DISCUSSIONS

The author has not yet completed quantitative estimation on various effects concerning to the cross-coupling in the bunch compressor, beam divergence, energy spread, photo-emission and CSR effect. Therefore the discussions below are only conceptual.

- The seeded FEL does not require high peak current. If we can lower the peak current, all problem associated with the space charge will be solved.
- Recently, strong OTR radiation was observed at visible wavelength in the LCLS injector at SLAC when the beam was compressed at the first chicane magnets[8]. If the laser on the photo-cathode has intensity modulation, which generates density modulation on the emitted electron beam. When the bunch length is compressed in the chicane, the modulation wavelength was compressed from micron-meter range to visible wavelength, as just we discussed in this paper. Further careful analysis is necessary to proof this hypothesis.

CONCLUSIONS

New optical modulation scheme has been proposed in this paper. If we apply velocity modulation at optical wavelength, and compress it together with bunch length, we may obtain density modulation at shorter wavelength.

Further studies are required on non-linear field in bunch compressor, cross-coupling (R_{15}, R_{16}), non uniform velocity distribution in bunch, energy spread due to radiation excitation, etc.

SCSS test accelerator is currently running at 50 nm with SASE-FEL mode. It will be possible to install a laser modulator in our test accelerator to demonstrate velocity modulation, and demonstrate colour change in OTR radiation, and compress the wavelength by ten times in bunch compression to seed FEL at 50 nm range.

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