MOCAU04: Focal Point Laser-Field as Optical Seeder

Tsumoru Shintake, RIKEN/SPring-8

- Back to the FFTB
- System Diagram
- Thermal diffusion problem
- How does it works
- Wavelength compression
- Atto-second X-ray
  - Femto-sec pulse at optical wavelength.
Nanometer Beam Size Measurement

e+e- Linear Collider R&D

Spot-size Monitor based on Laser Interferometry

Interferometer

YAG - Laser

Compton Scattered γ-ray flux

γ-ray Detector

Magnet

Electron Beam

Steering Magnet

Laser Interference Fringe

T. Shintake 1990

PHYSICS TODAY
JULY 1994
Experimental Test at FFTB

SLAC Two-mile Accelerator & FFTB

Laser Interferometer Table

KEK-Kawasaki

2-mile Linac (3.2 km)
Laser modulation system
How does it work?

Laser Modulation and Wavelength Compression

Laser Modulation

Wavelength Compression

Super-Radiation

Electron Beam

Mirror

Compressor

Accelerator

Undulator

Full Coherent X-ray

Bunch Compression

"Laser Modulation"
T. Shintake, PAT Application
JPN 2005-238112

"Wavelength Compression"
T. Shintake, 1999
KEK AccLab-99-1
T. Shintake, FEL2006

Thermal Diffusion Near Cathode

Can we use “Laser induced modulation on the cathode”, as seeder?

- Thermal kinetic energy.

\[
\left \langle \frac{1}{2} m_e v_z^2 \right \rangle = \frac{1}{2} kT = 74 \text{ meV} \quad \text{at } 1500 \text{ deg.C}
\]

- Constant acceleration on \( E_z \). (relativistic energy conservation)

\[
W_k(z) = eE_z \cdot z + W_{th}
\]

\( z \) : distance from cathode.

\( W_k(z) \): kinetic energy at position \( z \).

\( W_{th} \): thermal energy at cathode.

- Thermal Diffusion (see graph in next page)
  - \( t_1 = 45 \text{ fsec} \)
  - \( C t_1 = 14 \mu \text{m} \)
  - \( Z_1 = 3.7 \text{ nm} \)

at 20 MV/m

\[
\Delta z = ct_1 - Z_1
\]

\[
ct_1 = \frac{m_0 c^2}{eE_z} \sqrt{\frac{2W_i}{m_0 c^2}}, \quad Z_1 = \frac{W_i}{E_z}
\]

Even if you run your rf-gun at 100 MV/m, the thermal diffusion becomes 3 \( \mu \text{m} \). It is still longer than optical wavelength. Thus, optical modulation, induced by laser field on the cathode, will smear out.
Thermal Diffusion from Cathode

Estimation of position difference for two electrons: zero initial velocity and with thermal velocity.

Thermal diffusion effect dominates near the cathode.
Thermal Diffusion at Relativistic Energy.

• Thermal Diffusion during acceleration.
  – Initial velocity and energy: $\beta_1$, $\gamma_1$
  – Final velocity and energy: $\beta_2$, $\gamma_2$
  – Accelerating field: $E_z$

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

$$\gamma' = \frac{eE_z}{m_0 c^2}$$

• Criterion to maintain modulation

$$\Delta z_{th} < \frac{\lambda_{mod}}{4}$$

• Example case.
  – $\lambda = 200$ nm, $T = 1500$ C, $kT/2 = 74$ meV, final energy 8 GeV
  – Acceleration 20 MV/m
  – Required minimum energy: 4.4 keV, this is quite low (0.2 mm from cathode)
  – If you located laser modulator after this energy, the modulation will kept up to very high energy.
Standing laser field modulates beam energy.

Use longitudinal electric field as energy modulator.
Creation of density modulation

- Laser field
- Velocity modulation
- Micro-bunching
- Electron beam
- Beam current
- Free drift
- \( \lambda / 2 \)
- \( \beta \lambda / 2 \)
If the laser spot size is large, the laser field coupling becomes small, due to transit-time constant lowered.

Need, small laser spot size.

\[ \sigma_z / \lambda < 0.5 \]
High numerical aperture. NA~1

\[ \sigma_z = \frac{\lambda}{\pi \theta} \]

\[ NA = n \cdot \sin \theta \]

\[ F = \frac{f}{D} \approx \frac{1}{2NA} \]

High NA > 0.5 is commercially available.
## Example beam parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>YAG-Laser 2</strong>&lt;sup&gt;nd&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>Output power</td>
<td></td>
</tr>
<tr>
<td><strong>Focusing</strong></td>
<td>Cylindrical lens</td>
</tr>
<tr>
<td>Focusing length</td>
<td>$f$</td>
</tr>
<tr>
<td>Numerical aperture</td>
<td>NA</td>
</tr>
<tr>
<td>Matched laser beam size</td>
<td>$\sigma \sim 0.5D$</td>
</tr>
<tr>
<td>Focused spot size</td>
<td>$\sigma_{z0}$</td>
</tr>
<tr>
<td>Transverse width</td>
<td>$\sigma_{x0}$</td>
</tr>
<tr>
<td>Field intensity</td>
<td>$E_{z0}$</td>
</tr>
<tr>
<td><strong>Modulation</strong></td>
<td></td>
</tr>
<tr>
<td>Modulation period</td>
<td>$\lambda_{mod}$</td>
</tr>
<tr>
<td>Coupling Constant</td>
<td>$C_{couple}$</td>
</tr>
<tr>
<td>Modulation Energy</td>
<td></td>
</tr>
</tbody>
</table>
Wavelength Compression
on Compressing Electron Bunch

T. Shintake
KEK: High Energy Accelerator Research Organization
Wavelength Compression?

Seeding Laser

Energy Modulation

1st-Undulator

Bunch Compression

RF Cavity

Short Wavelength Coherent Radiation

Dispersion

RF Acceleration

2nd-Undulator
Micro-Energy Spread

$\sigma_E / E \sim 10^{-7}$ or $\sigma_E \sim 10^{-7} E$

$AE \sim 0.1 \text{ }$ %

$AE \sim 0.1 \text{ }$

Local

$\Delta E \sim m \cdot \lambda_1 \sim 100 \times 266 \text{nm} \sim 30 \mu m$

$\frac{\Delta \lambda}{\lambda} \sim \frac{1}{m} \sim 1\%$

1 mm bunch
Electron Energy Spread.

\[ \sigma_e \leq \pi \cdot \frac{\lambda_z}{\lambda_{rf}} \cdot V_{rf} \]

\[ \alpha \]

\[ \lambda_z > \frac{\lambda_{rf}}{\pi} \cdot \frac{\sigma_e}{V_{rf}} \]

Example: \( V_{rf} \sim 100 \text{ MV} \)
\( \lambda_{rf} \sim 50 \text{ mm} \)

<table>
<thead>
<tr>
<th>( \lambda_z ) (nm)</th>
<th>100</th>
<th>50</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_e ) (eV)</td>
<td>600</td>
<td>300</td>
<td>60</td>
</tr>
<tr>
<td>( \delta e/E )</td>
<td>( 4 \times 10^{-6} )</td>
<td>( 2 \times 10^{-6} )</td>
<td>( 4 \times 10^{-7} )</td>
</tr>
</tbody>
</table>
Longitudinal spread of modulation pattern after compression due to thermal energy spread.

\[
\sigma_z^* = \frac{\lambda_{rf}}{2\pi} \frac{\sigma_e}{\lambda_x} < \frac{\lambda_x}{4}
\]

Required rf voltage.

\[
V_{rf} > \frac{2}{\pi} \frac{\lambda_{rf}}{\lambda_x} \sigma_e
\]

\[
\lambda_{rf} = 50 \text{ mm. C-band}
\]

\[
\lambda_x = 0.1 \text{ mm. X-ray}
\]

\[
\sigma_e = 0.1 \text{ eV, thermal energy spread}
\]

\[
V_{rf} > 50 \text{ MV}
\]

This is quite easy value.
Can we generate coherent X-ray at 0.1nm?

- Need **1000** times compression.
  200 nm laser $\rightarrow$ 100 nm modulation $\rightarrow$ 1/1000 $\rightarrow$ 0.1 nm

- In **SCSS test accelerator**, already x **800** compression has been achieved (cathode 1 A $\rightarrow$ undulator 800 A)

- 1/10 times velocity compression
- 1/100 times chicane magnetic compression (x20 at BC1, X 5 at BC2)
- Modulation depth of 1 % is good enough to seed FEL.
  - Wake field, CSR, SR, non-linear will break modulation, but, if 1 % remains, still OK.
Generation of Attosecond\textsuperscript{(10^{-18})} X-ray

- Femtosecond TiSa Laser for optical modulation

100 femtosecond $\rightarrow$ 1/1000 times compression

$\rightarrow$ 100 attosecond radiation
Conclusion

- Focal point field modulates electron energy at optical wavelength.
- Thermal diffusion looks no problem. OK.
- High compression ratio will request stable power supply for rf-system.
- Seeding to X-ray FEL will be possible.
- Need beam test at VUV. SCSS test accelerator.