FORMATION OF ELECTRON BUNCHES FOR HARMONIC CASCADE X-RAY FREE ELECTRON LASERS

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Harmonic cascade FEL


Fresh electron technique

Relatively long electron bunch is needed
Basic requirements to the e-beam

Relatively long bunch $\sim 0.5 – 1$ ps with “flat” peak current distribution

Small emittance

$$\varepsilon \approx \gamma \lambda_{x-ray} / 4\pi$$

Small energy spread (for better bunching):

$$b_n \sim e^{-\frac{1}{2} \left( \frac{n^2 \pi}{\lambda} \frac{R_{56} \sigma_E}{2} \right)^2}$$

High peak current (for better FEL gain):

$$L_{gain} \sim \frac{1}{(I_{peak})^{1/3}} \text{ or } \frac{1}{(I_{peak})^{1/2}}$$
Basic requirements to the e-beam (2)

One of the goals for HC FELs is production of nearly FT limit signal with a narrow BW

Two examples using two different electron beams

Quadratic energy chirp

Elegant

Δ\(w_{\text{FWHM}}\) ≈ 40 meV

“Flat”

Power spectrum (courtesy G. Penn)

Δ\(w_{\text{FWHM}}\) ≈ 10 meV
Basic requirements to the e-beam (3)

Energy variation along the electron bunch causes frequency chirp in the output signal* 

\[ \frac{\Delta E}{E} \sim a z^2 \]

Quadratic energy chirp with superimposed energy modulation in the modulator

Compression factor:

\[ C = \frac{1}{1 + h R_{56}}; \quad h = \frac{d(\Delta E/E)}{dz} \]

\[ \overline{C} \approx 2a R_{56} z \]

More compression at the tail than at the head produces electron bunch with modulated density \( \omega_{\text{head}} < \omega_{\text{tail}} \)

Reverse tracking

Flat-flat distribution is desirable at the end of the accelerator

A distribution at the beginning of the accelerator that will evolve into flat-flat distribution can be found using reverse tracking*
Reverse tracking: justification

1) Over the linac section relative electron positions are “frozen” and electron energy at the beginning $\delta_i$ is defined by electron energy and location at the end $\delta_f(z_f)$

$$\delta_f(z_f) = \delta_i(z_i) + eU \cos (k z_i + \phi) - Q \int_{z_i}^\infty w(z - z') \lambda_z(z') dz'$$

* wake function
* density function

2) Over the magnetic chicane (buncher) electron energy is “frozen” (CSR excluded) and electron coordinate at the beginning $z_i$ is defined by the electron coordinate and energy at the end $z_f(d_f)$

$$z_f(\delta_f) = z_i + R_{56} \delta_i + T_{566} \delta_i^2 + f_{CSR}(z_i, \delta_i)$$
Reverse tracking: ignore CSR

Shielding of CSR by the vacuum chamber

\[ \frac{\Delta E_{\text{shielded}}}{\Delta E_{\text{free space}}} \]

\[ \text{gap } = 8 \text{ mm} \]

For “long” bunches energy losses due to CSR are weak at \( \omega \sim \frac{1}{\tau_b} \)

Reverse tracking: use of wake fields

**Begin tracking**

End of accelerator

**End tracking**

Start of accelerator

Wake potential: \( W(s) = -\int_{s_0}^{\infty} w(s-s')\lambda_z(s')ds' \) where \( w(s) = A\frac{Z_0 c}{\pi a^2} L \exp\left(-\sqrt{s/s_0}\right) \)

Peak current from injector (A)

Ideal

Practical

Ramped peak current

LiTrack: no LSC no CSR

A. Zholents, Edinburgh, June 2006
From ramped to flat peak current

\[ I_b = I_{b0} + s I'_b \]

\[ I_a = I_{a0} \]

\[ h = \frac{d(\Delta E / E)}{dz} \]

\[ C = \frac{1}{1 + hR_{56}} = \frac{I_a}{I_b} \]

\[ C^{-1} = \frac{I_{b0} + s I'_b}{I_{a0}} = 1 + h_0R_{56} + h'R_{56}s \]

Small quadratic energy chirp is used

\[ h = h_0 + h's \]

\[ I_b = I_{b0} + s I'_b \]

\[ h' = \frac{1}{R_{56}} \frac{I'_b}{I_{a0}} \]
Reverse tracking: practical distribution

Photocathode laser is used to shape the electron distribution in the e-gun

Next to the cathode

At the end of the injector at 100 MeV

For HC FEL, larger emittance in the tail may not be a problem and smaller emittance at the head can be beneficial.
Current spikes: the origin

Before bunch compressor

Typical parabolic peak current distribution

After bunch compressor

Typically in the bunch compressor

bifurcation: due to \( d^3E/dz^3 \) and \( T_{566} \)

\[
h_0 = \frac{dE}{dz} \neq 0; \quad h' = \frac{d^2E}{dz^2} \approx 0; \quad h'' = \frac{d^3E}{dz^3} \neq 0
\]

using x-band linearizer

\[
T_{566} \approx -\frac{3}{2} R_{56}
\]
Current spikes and their removal

Cubic chirp = -8 keV/mm$^3$

Cubic chirp = -90 keV/mm$^3$

Cubic chirp can be adjusted with small modification in the electron density distribution which alters the wake fields
Current spikes and their removal (2)

Adjustable $R_{56}$ using trim quadrupoles to provide dispersion bump

LINAC

“dog-leg” section

$R_{56}=2.8$ mm

$R_{56}=7$ mm
Complete simulation

Example of flat-flat distribution taken from accelerator optimization study for FERMI@ELETTRA FEL* (CSR included)

*) M. Cornacchia et al., MOPCH047, Edinburgh, June 2006
Electron density distribution in the gun and along the accelerator plays important role in formation of electron bunches at the end of accelerator.

Photocathode laser can be used to provide a distribution suitable for given wake potential, such as linear ramped peak current.

Peak current spikes at the edges of the electron bunch can also be affected.

Useful discussions with P. Emma and G. Stupakov are acknowledge. P. Emma also helped with LiTrack.
Thank you for your attention
DIPAC 2007
the 8th European Workshop on
Beam Diagnostics and Instrumentation for Particle Accelerator
May 2007
Jitter studies

samples of 10 randomly chosen seeds out of 400 seeds are shown

quadratic energy chirp: $E'' \approx (3 \pm 0.4) \text{ MeV/ps}^2$  

$E'' \approx (0.5 \pm 0.07) \text{ MeV/ps}^2$

to be compared with the requirement of $|d^2E/dt^2| < 0.2 \text{ MeV/ps}^2$