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

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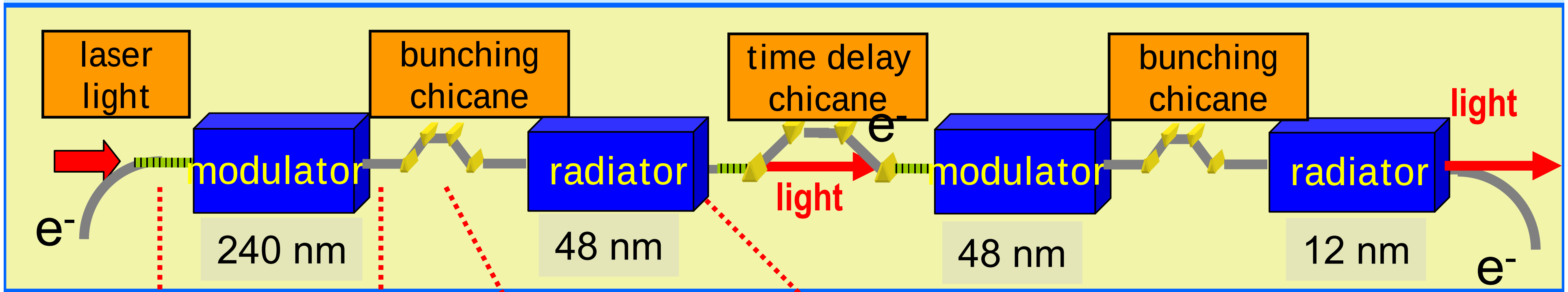
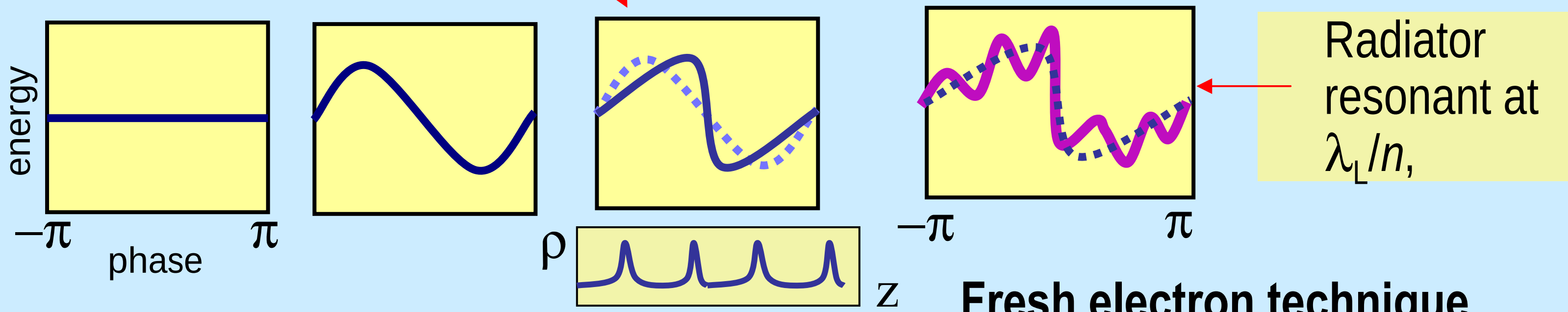
Harmonic cascade FEL*

*) Csonka 1980; Kincaid 1980; Bonifacio 1990; L.-H. Yu 1990

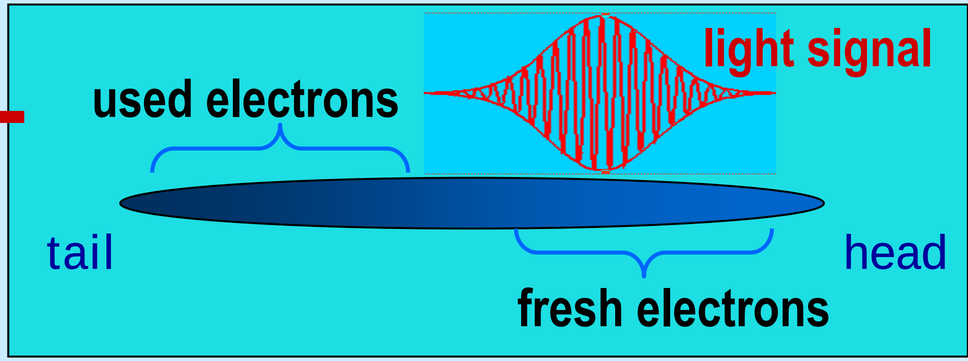


evolution of e-beam phase space



Relatively long electron bunch is needed

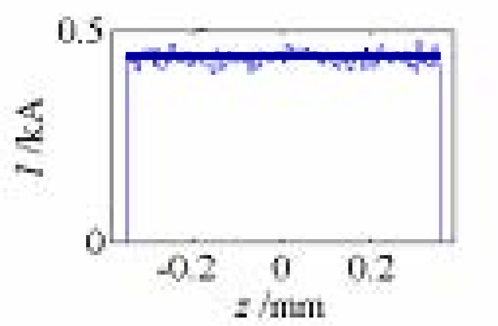
Fresh electron technique



A. Zholents, San-Diego, April, 2004

Basic requirements to the e- beam

Relatively long bunch ~ 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):

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

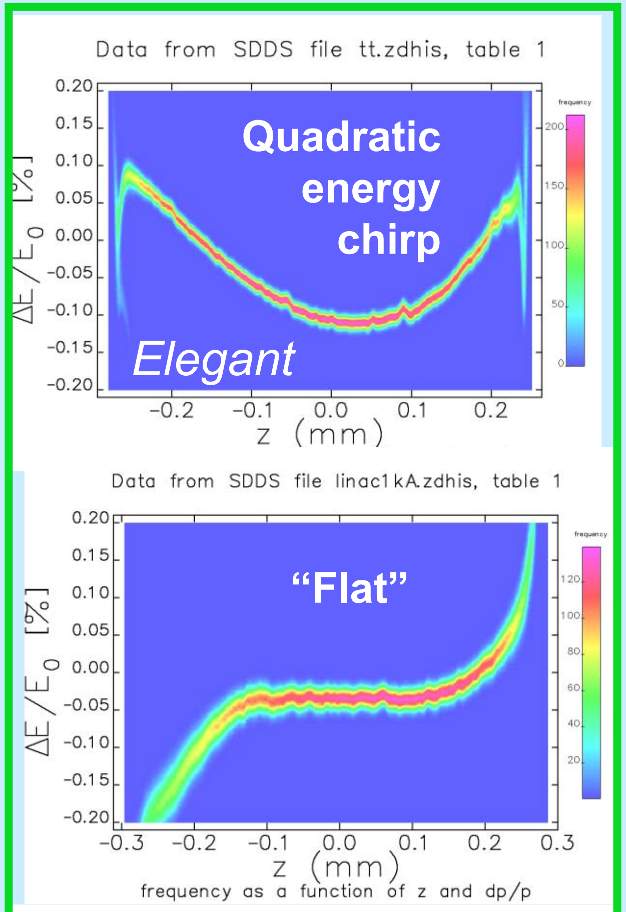
High peak current (for better FEL gain):

$$L_{gain} \sim \frac{1}{\left(I_{peak}\right)^{1/3}} \text{ or } \frac{1}{\left(I_{peak}\right)^{1/2}}$$

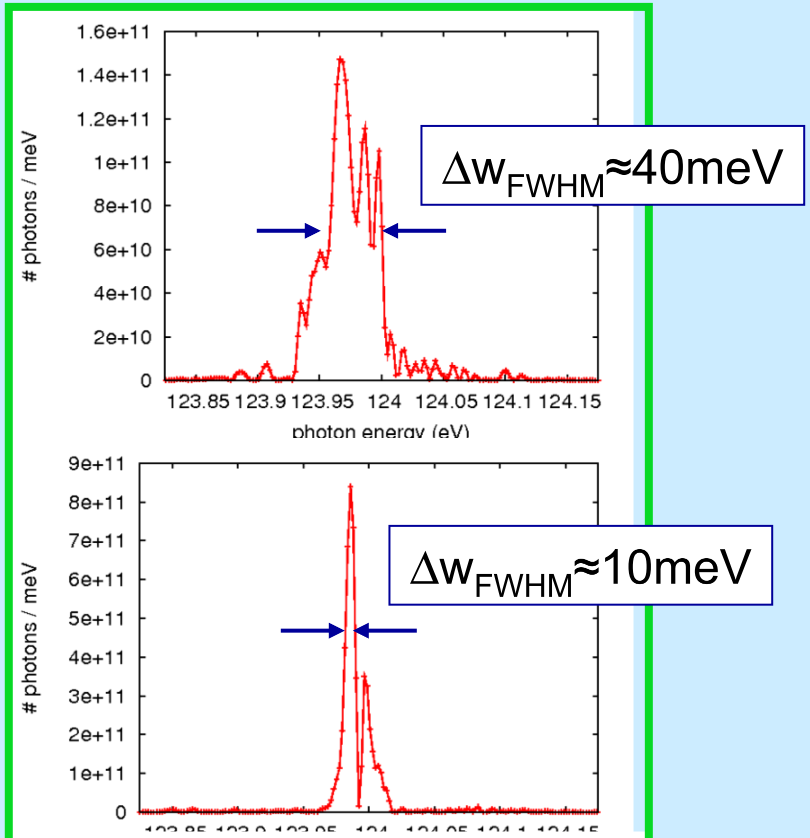
Basic requirements to the e- beam (2)

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



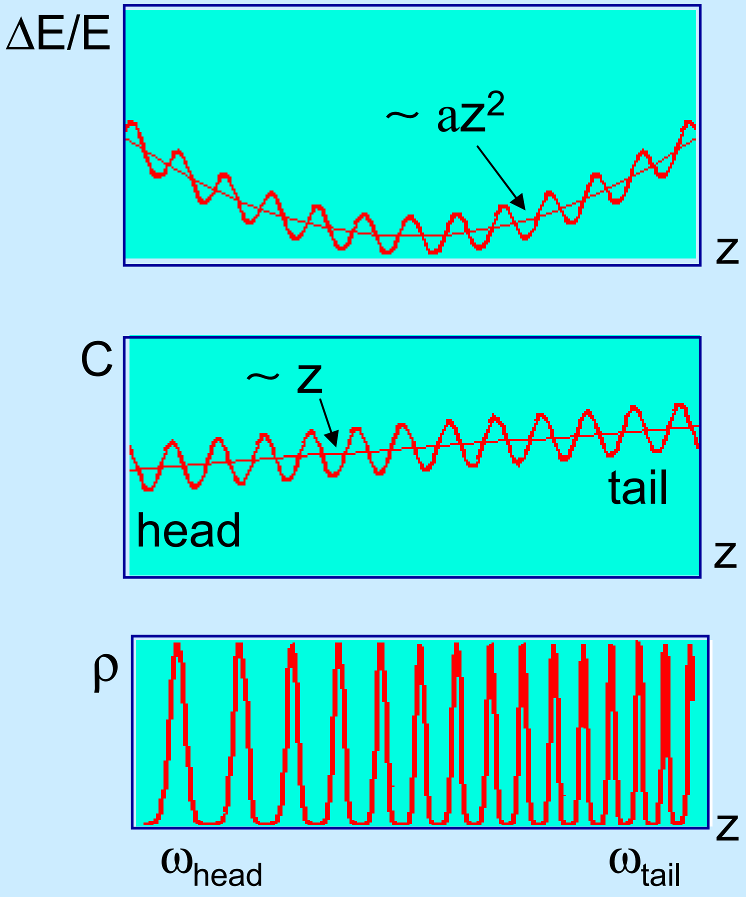
Longitudinal phase space



Power spectrum (courtesy G. Penn)

Basic requirements to the e- beam (3)

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



Quadratic energy chirp with superimposed energy modulation in the modulator

Compression factor:

$$C = \frac{1}{1 + hR_{56}}; \quad h = \frac{d(\Delta E / E)}{dz}$$

will also be used latter

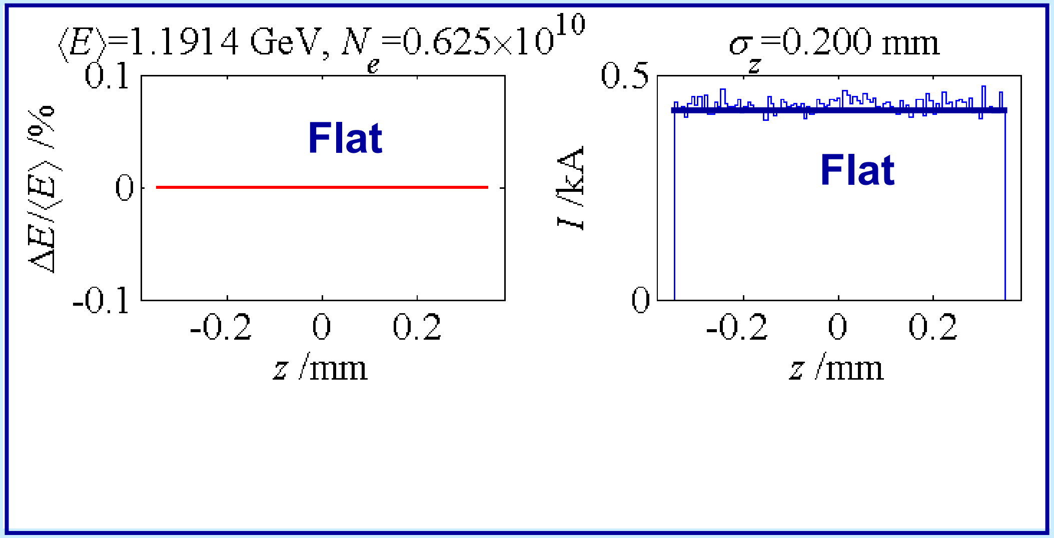
$$\overline{C} \approx 2aR_{56}z$$

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

*) S. G. Biedron, S.V. Milton, and H.P. Freund, NIM A **475** (2001)401.
T.Shaftan *et al.*, Phys. Rev. E, **71**, (2005)046501.

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*

*) M. Cornacchia

Reverse tracking: justification

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

wake function

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

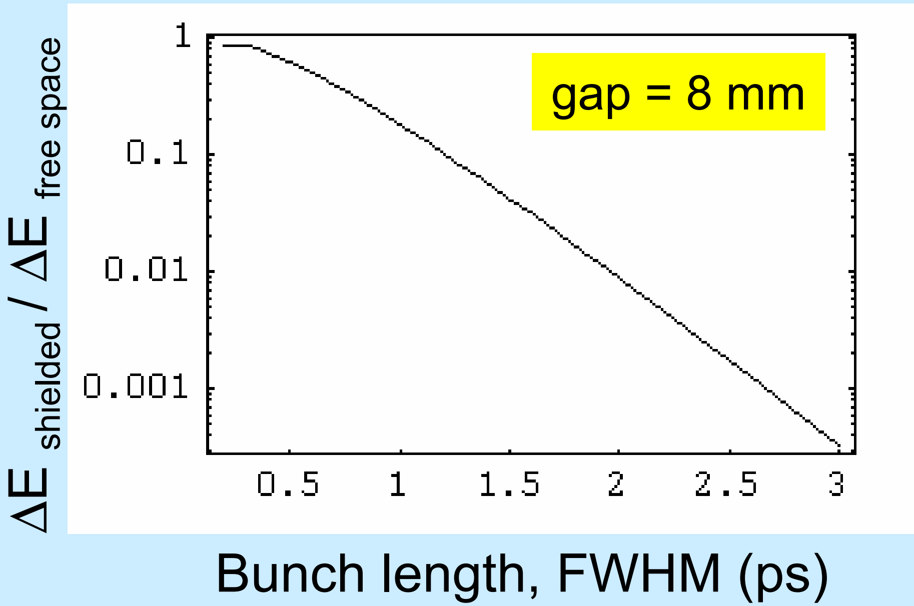
density function

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 $z_f(d_f)$

$$z_f\left(\delta_f\right) = z_i + R_{56}\delta_i + T_{566}\delta_i^2 + f_{CSR}\left(z_i, \delta_i\right)$$

Reverse tracking: ignore CSR

Shielding of CSR by the vacuum chamber*

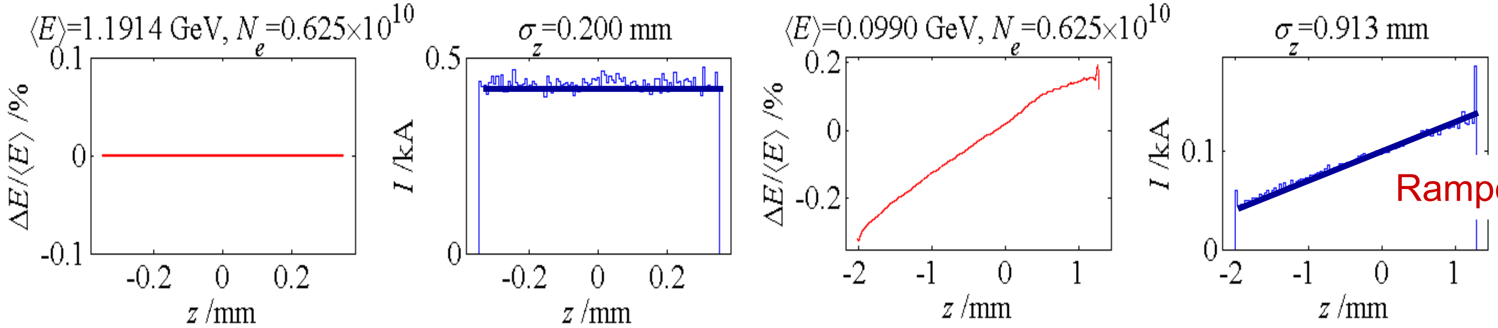


For “long” bunches energy losses due to CSR are weak at $\omega \sim 1/\tau_b$

*) R.Li, C.L. Bohn, J.J. Bisongnano, Proc. PAC 97, (1997)1644.

Reverse tracking: use of wake fields

Begin tracking | End tracking

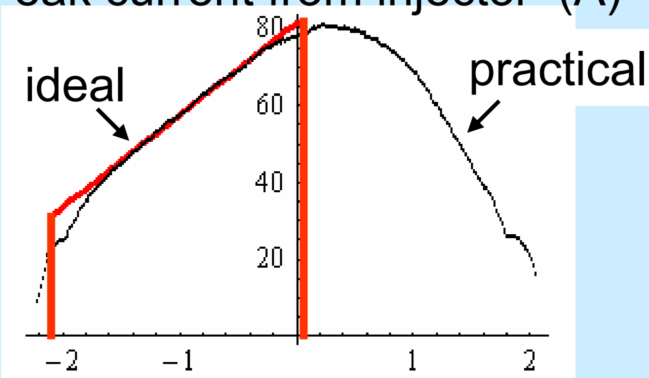


end of accelerator | start of accelerator

LiTrack: no LSC no CSR

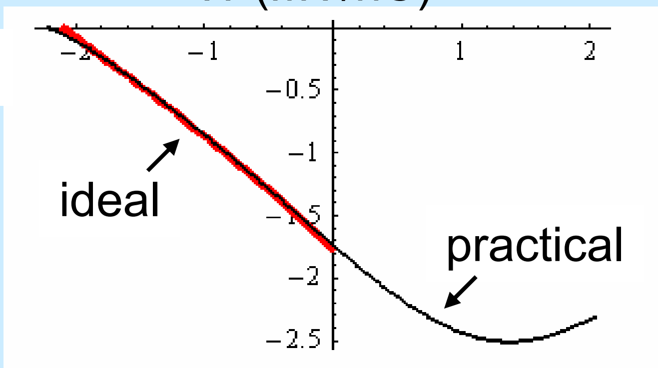
Wake potential: $W(s) = -\int_{s}^{\infty} w(s-s')\lambda_z(s')ds'$ where $w(s) = A\frac{Z_0 c}{\pi a^2} L \exp\left(-\sqrt{s/s_0}\right)$

Peak current from injector (A)



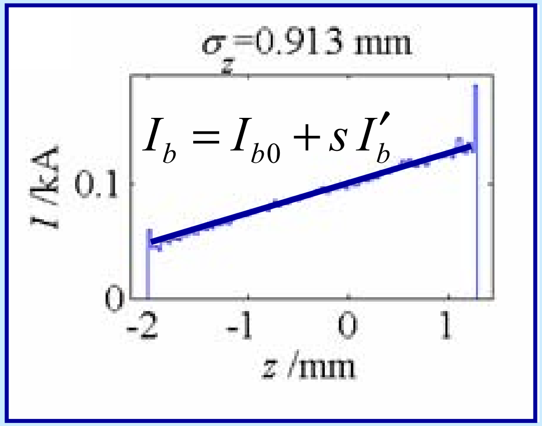
s (mm)

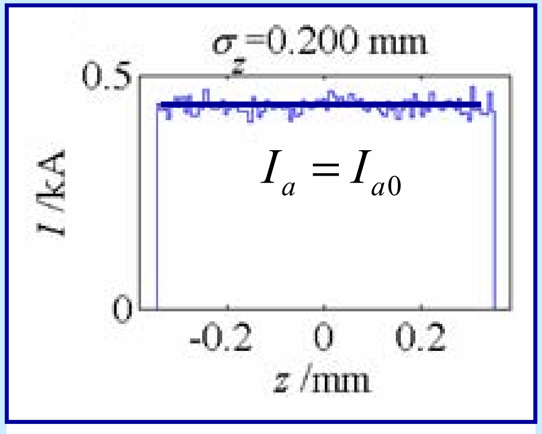
W (MV/nC)



s (mm)

From ramped to flat peak current





$$h = \frac{d\left(\Delta E / E\right)}{dz}$$

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

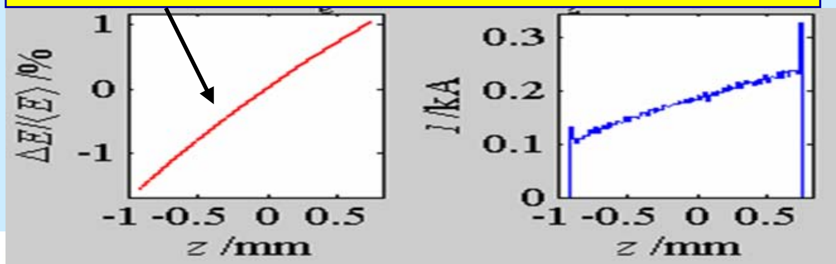
$$C^{-1} = \frac{I_{b0} + s\,I_b'}{I_{a0}} = 1 + h_0 R_{56} + h' R_{56} s$$

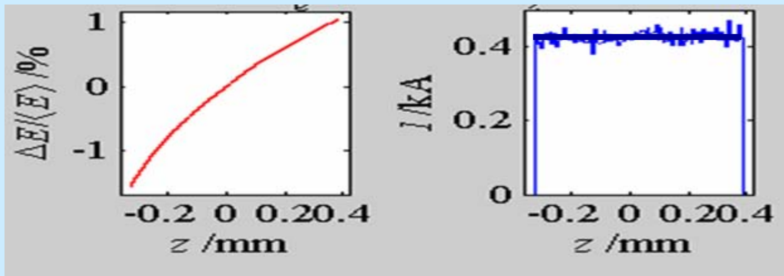
$h = h_0 + h's$

$I_b = I_{b0} + s\,I_b'$

$$h' = \frac{1}{R_{56}} \frac{I_b'}{I_{a0}}$$

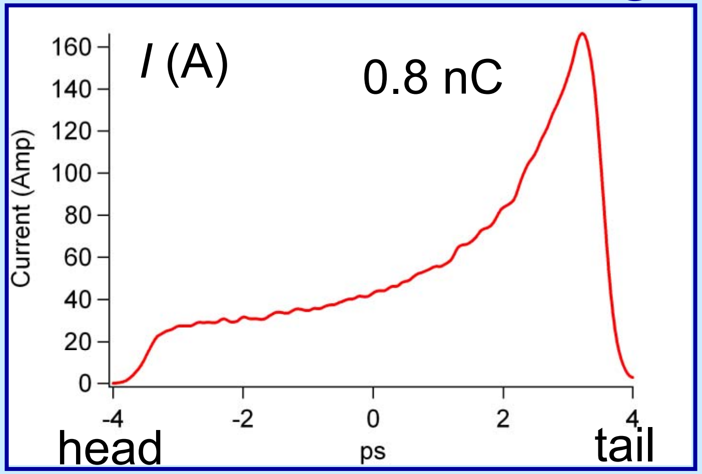
Small quadratic energy chirp is used





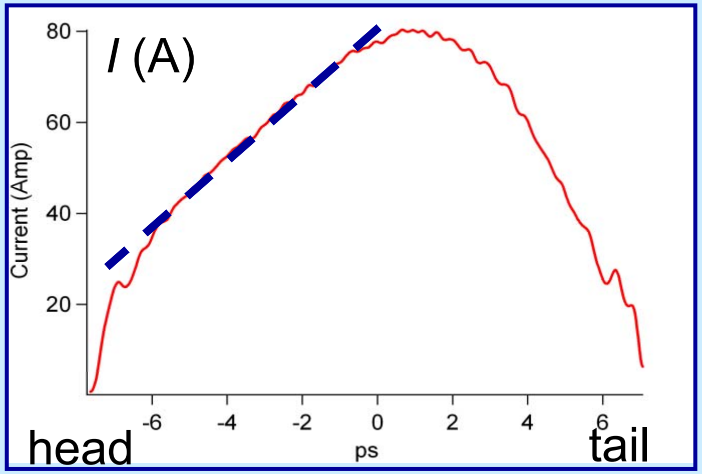
Reverse tracking: practical distribution

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

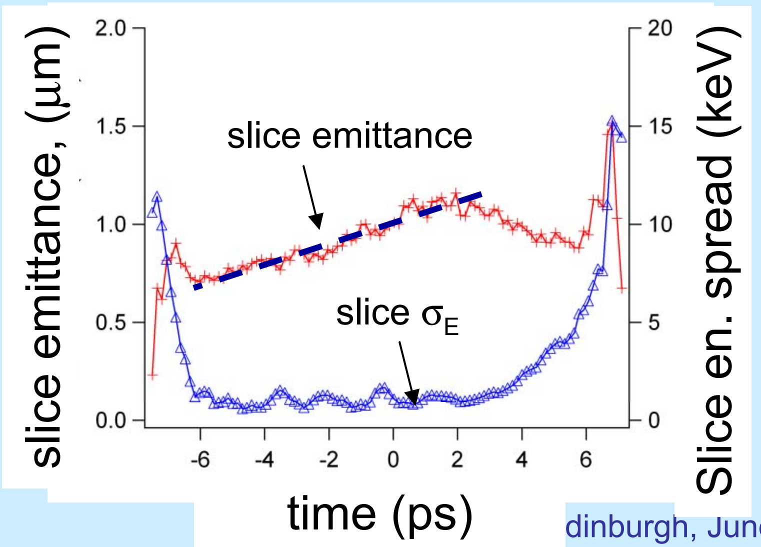


Next to the cathode

space charge



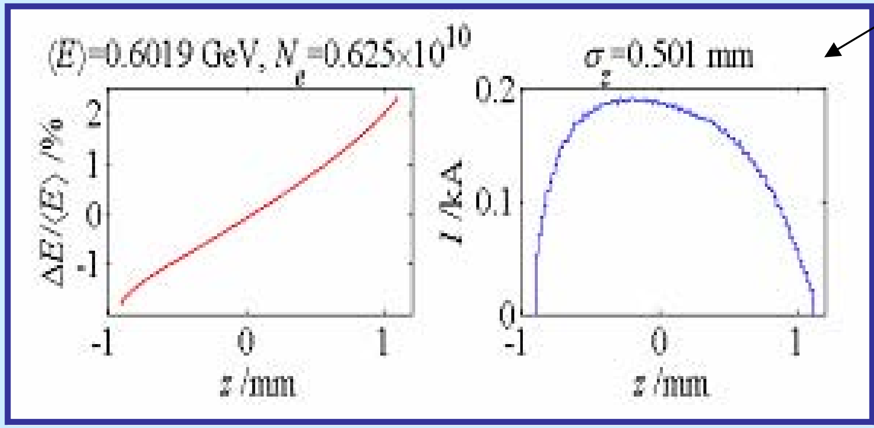
At the end of the injector at 100 MeV



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

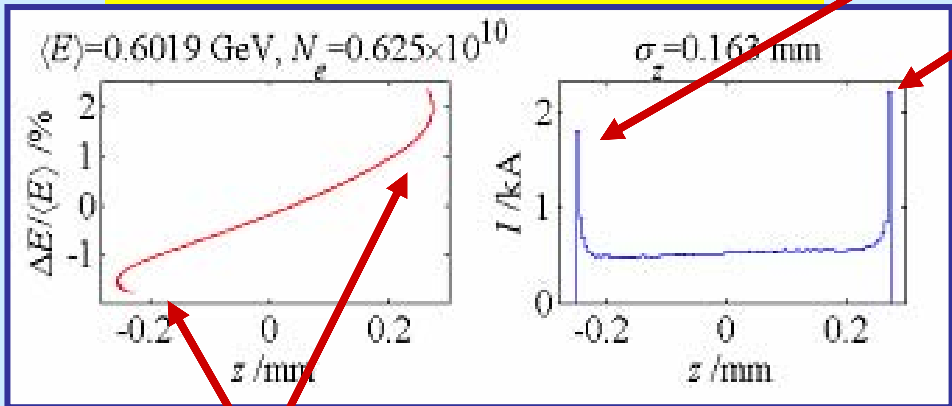


Typical parabolic peak current distribution

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

using x-band linearizer

After bunch compressor



spikes

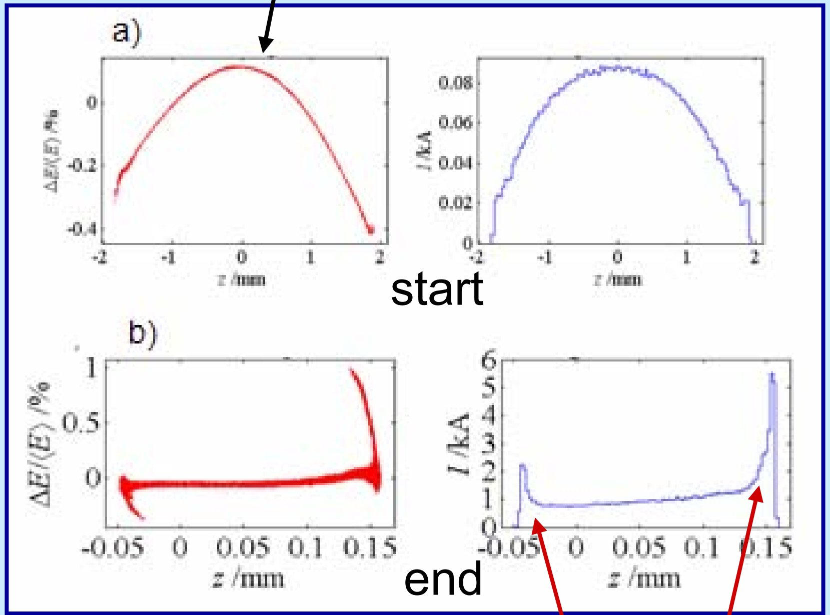
Typically in the bunch compressor

$$T_{566} \approx -\frac{3}{2} R_{56}$$

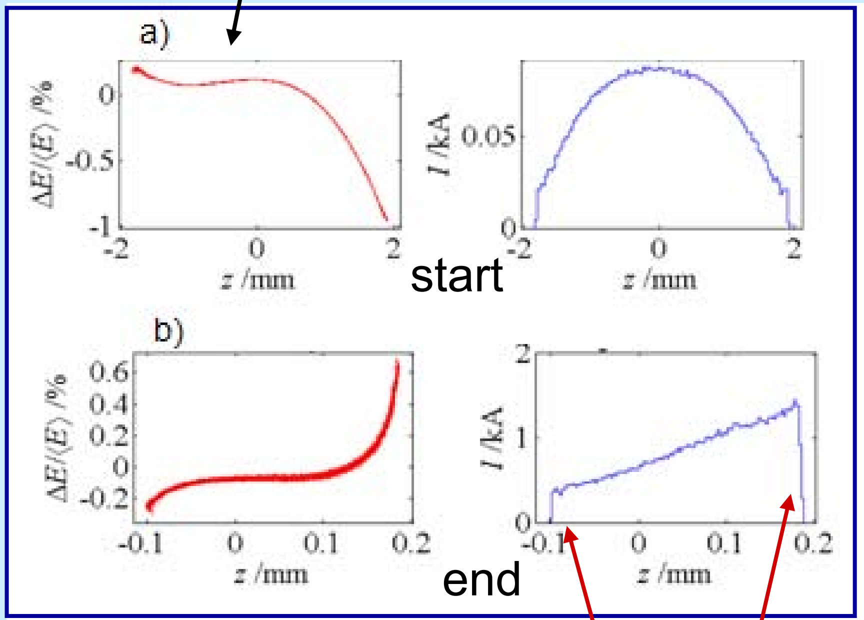
bifurcation: due to d^3E/dz^3 and T_{566}

Current spikes and their removal

Cubic chirp = -8 keV/mm^3



Cubic chirp = -90 keV/mm^3

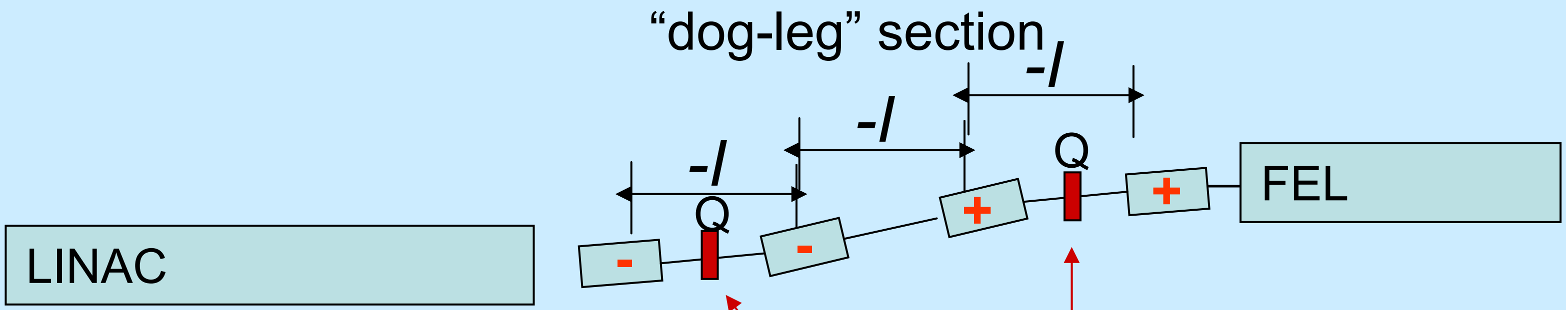


spikes

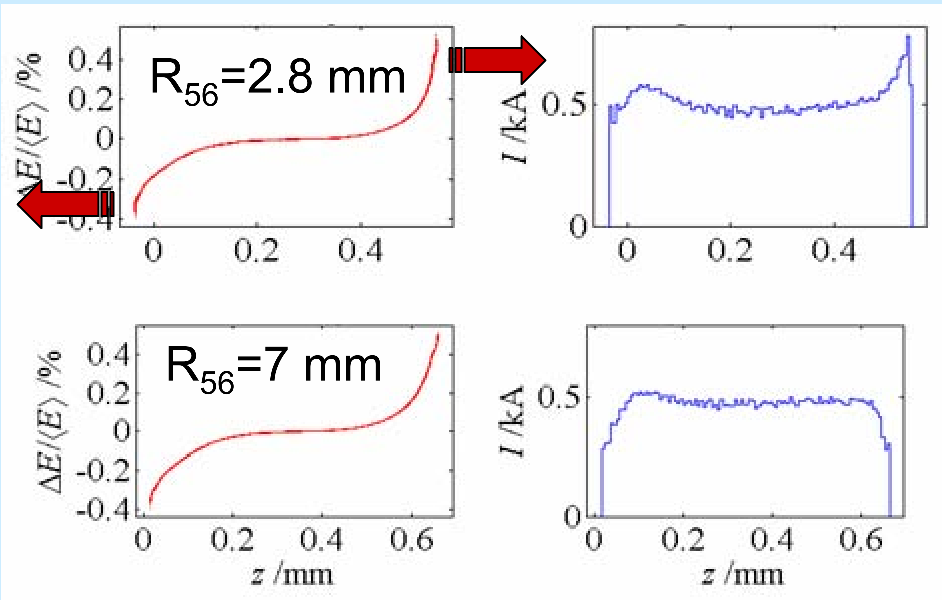
no spikes

Cubic chirp can be adjusted with small modification in the electron density distribution which alters the wake fields

Current spikes and their removal (2)

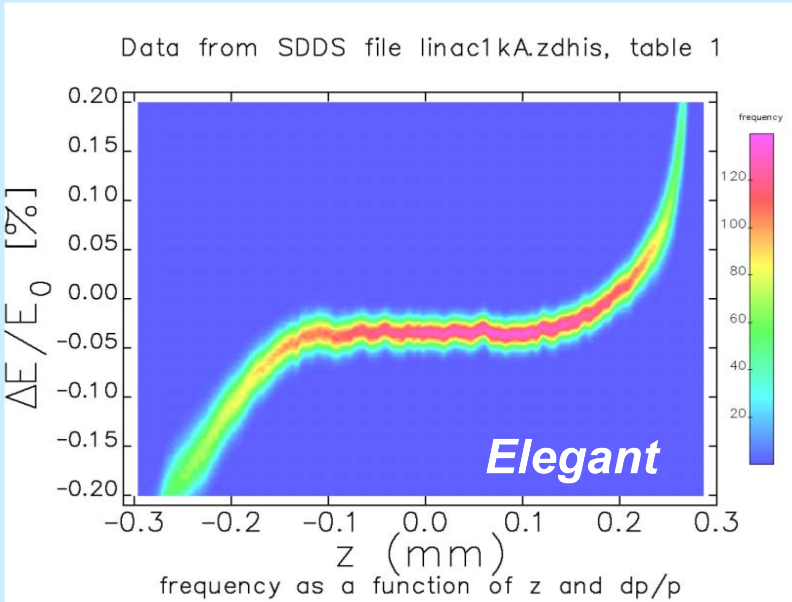


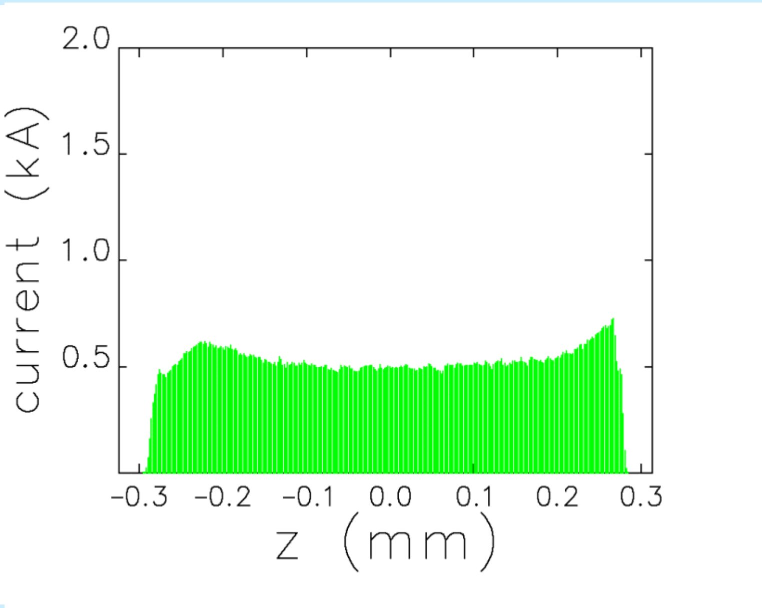
Adjustable R_{56} using trim quadrupoles to provide dispersion bump



Complete simulation

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





*) M. Cornacchia *et al.*, MOPCH047

Summary

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

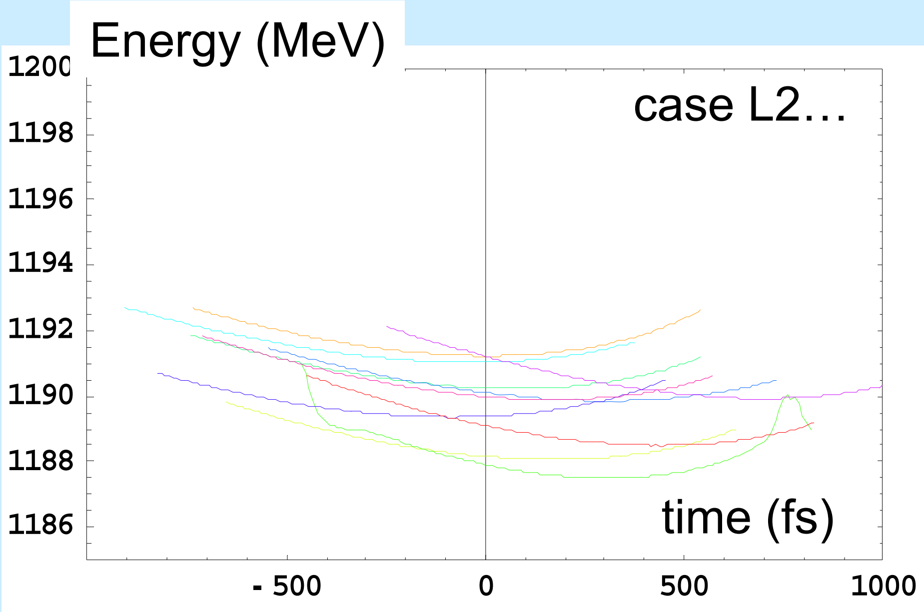
the 8th European Workshop on

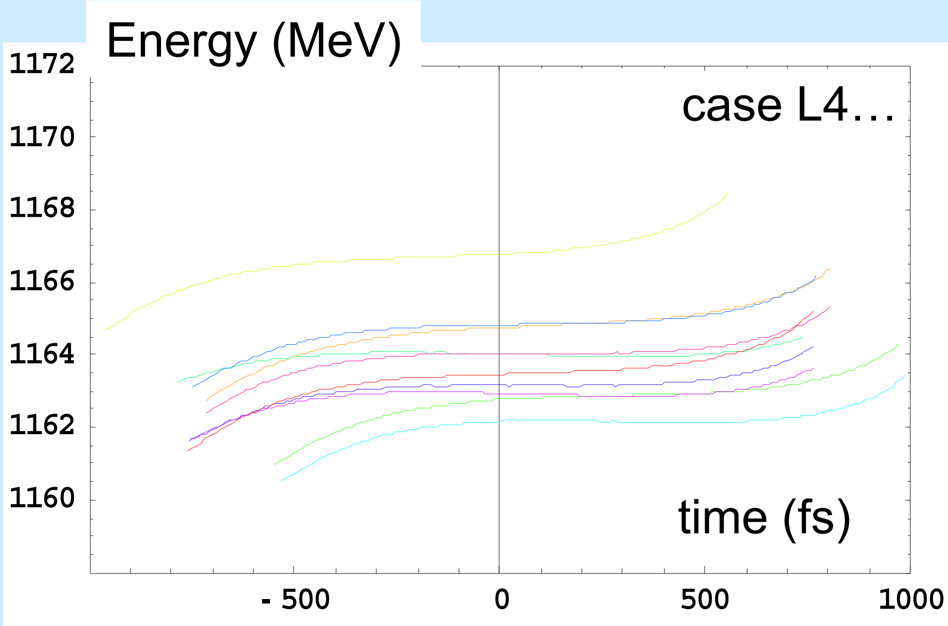
Beam Diagnostics and Instrumentation for Particle Accelerator

May 2007

Jitter studies

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





quadratic energy chirp: E'' ≈ (3 ± 0.4) MeV/ps^2 E'' ≈ (0.5 ± 0.07) MeV/ps^2

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