A simulation of XFELO operating in a scheme of velocity-bunching

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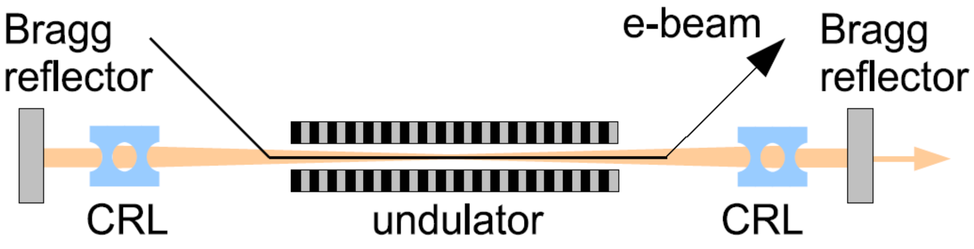
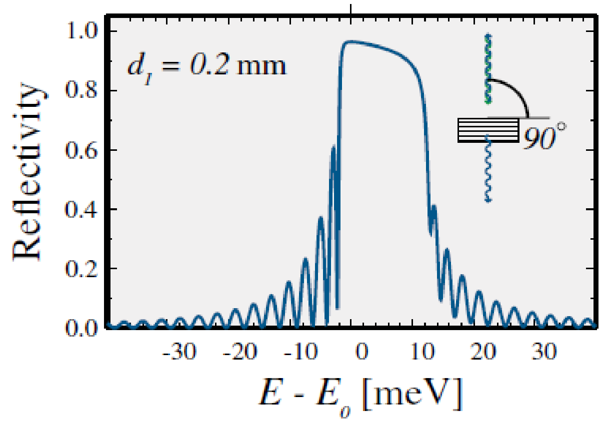
Outline

- 1-D FEL simulation
- XFELO in 7 GeV ERL
- XFELO in 5 GeV ERL with velocity bunching
- Summary

X-ray FEL Oscillator = XFELO

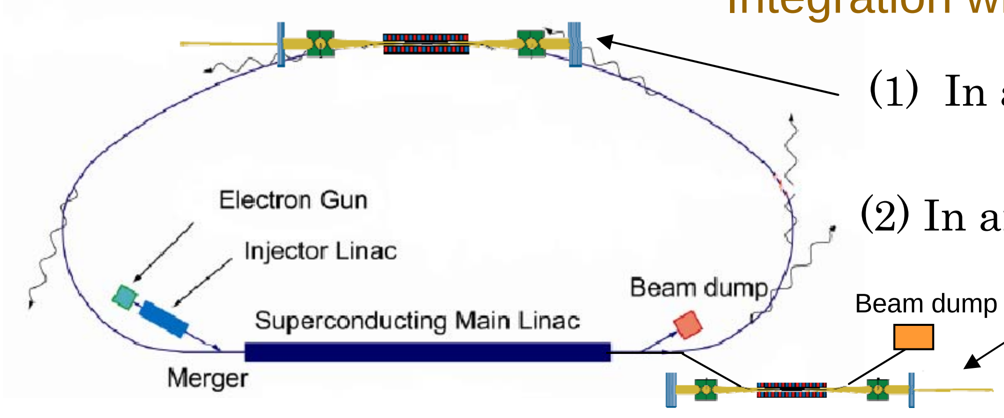




- lasing with 7 GeV, 20 pC, 1-100 MHz bunch
- fully coherent hard X-ray pulses
- average Brilliance = 10^{26}-10^{28}

K-J. Kim et al., PRL 100, 244802 (2008).

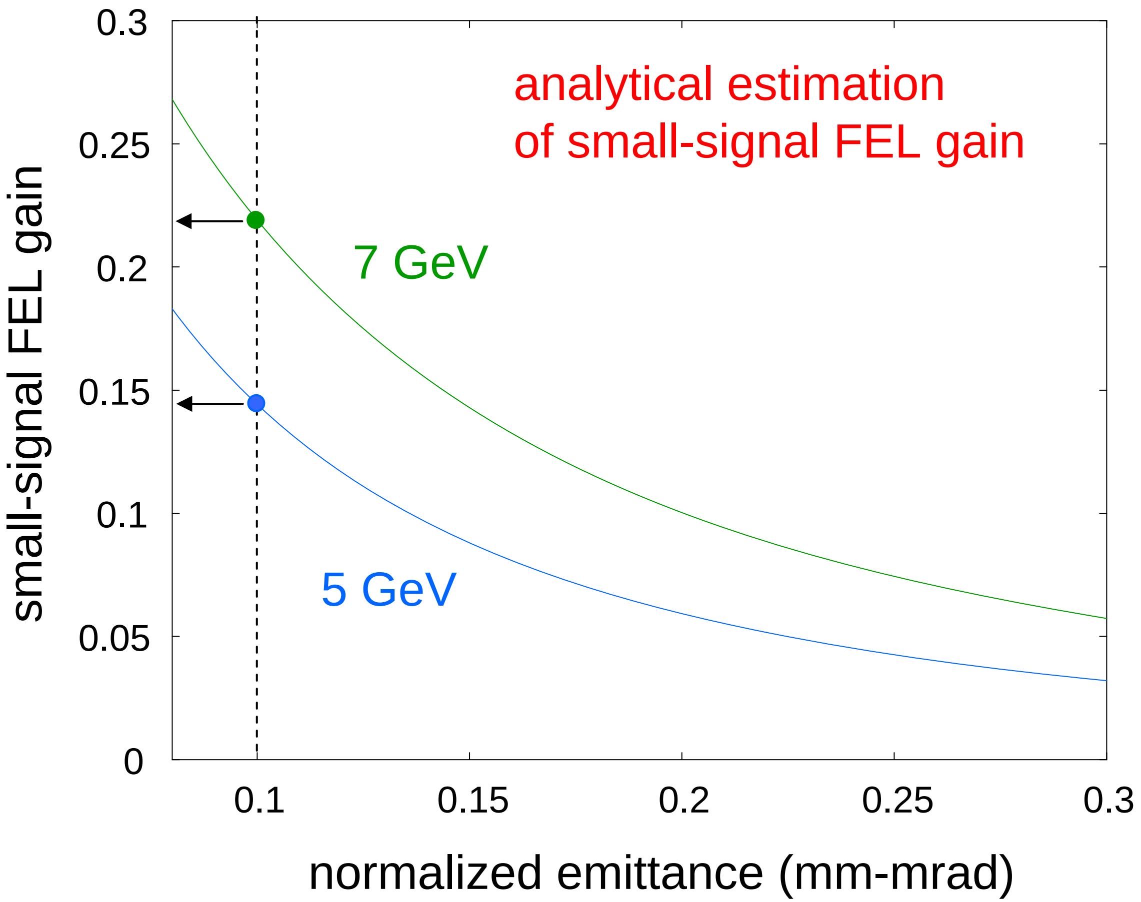
Integration with an ERL light source



(1) In a straight section of the loop

(2) In an additional single-ended branch

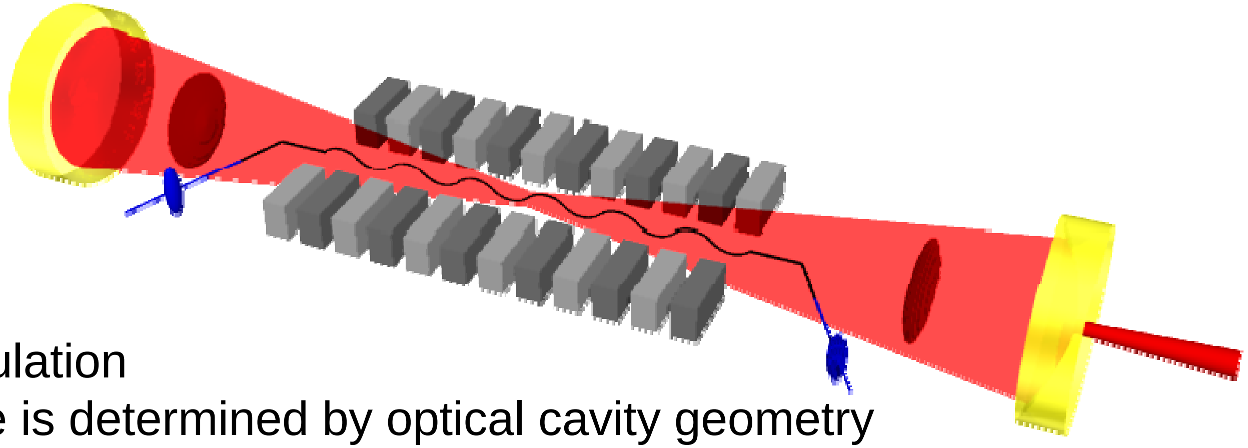
Small-signal gain of XFELO



1Å X-FELO

Energy	5 GeV	7 GeV
charge	20 pC	→
σ_t	2 ps	→
σ_E/E	1e-4	→
a_w	0.59	1.0
λ_u	1.43 cm	1.88 cm
N_u	3000	→
$\beta^*=Z_R$	10 m	→
ε_n	0.1 mm-mrad	→
gain	14 %	22 %

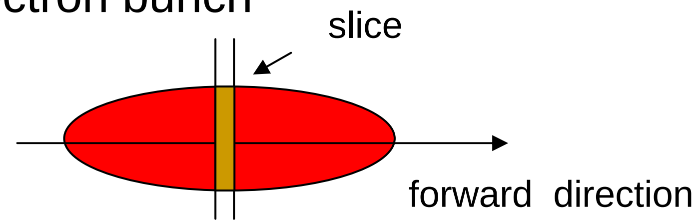
Simulation of FEL oscillator



1-D time dependent simulation
Optical transverse profile is determined by optical cavity geometry
Longitudinal mode is a function of cavity detuning length

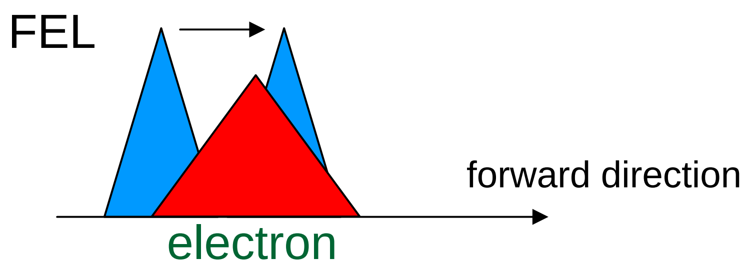
bunch-slice simulation

electron bunch



Periodic boundary condition

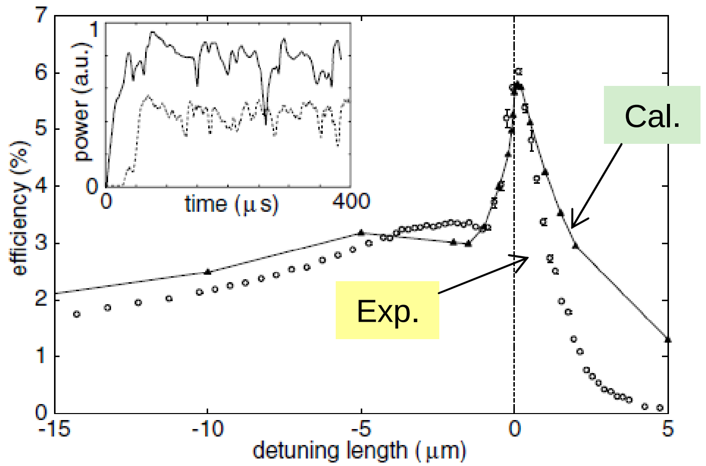
time dependent simulation



Electron bunch profile and slippage effect are taken into account.

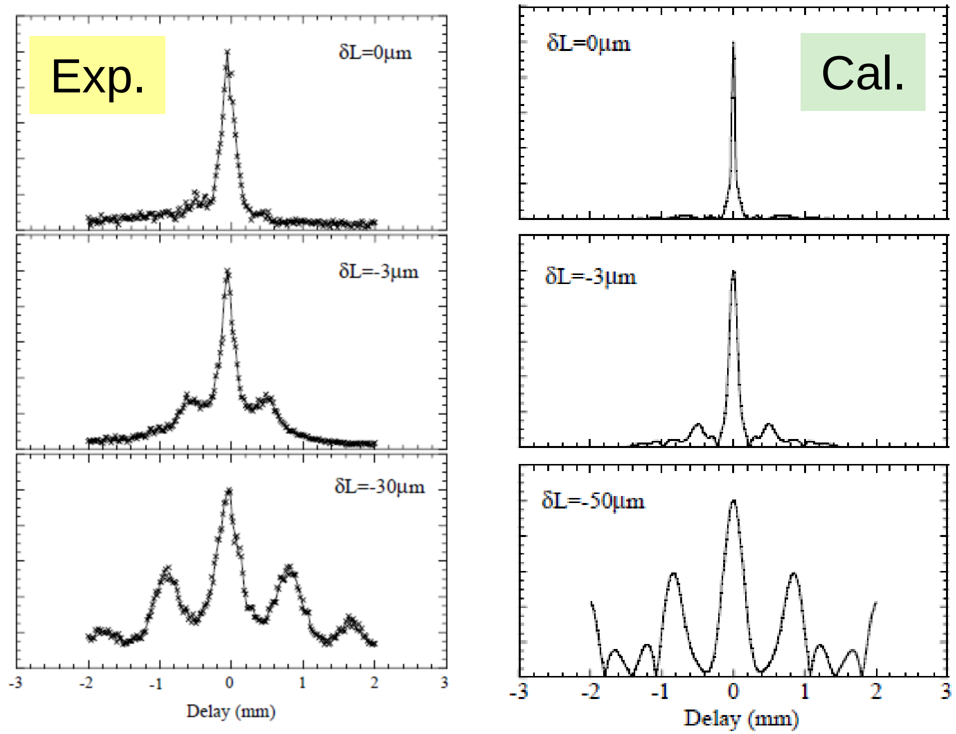
Simulation of an IR FEL oscillator

Examples for JAERI－FEL



FEL power as a function of dL

N. Nishimori et al., PRL 86, 5707 (2001)



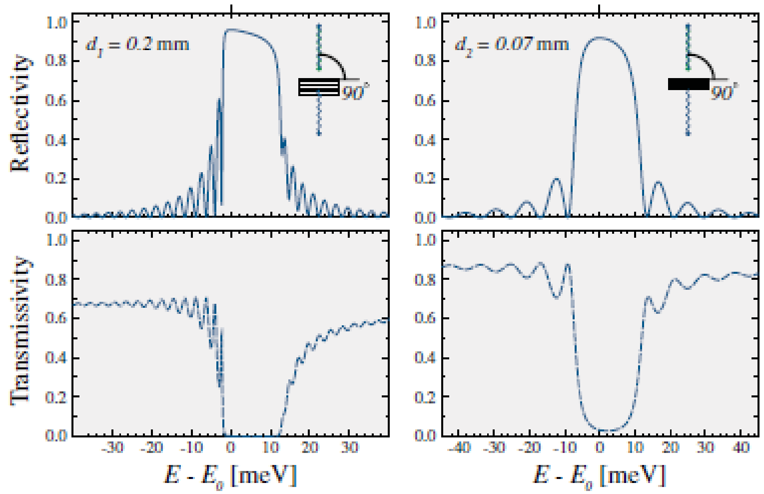
Autocorrelation of FEL pulse
as a function of cavity length

R. Nagai et al., NIMA 483, 129 (2002)

Extension of our simulation to XFELO

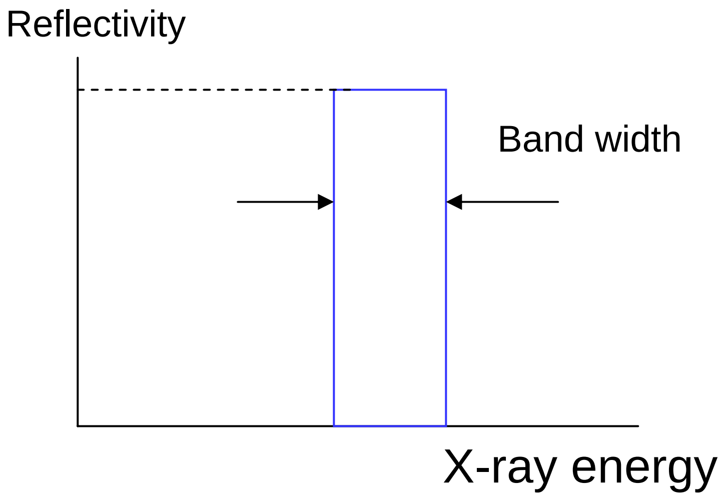
Narrow band reflector

Bragg reflection



K-J. Kim et al., PRL 100, 244802 (2008).

Frequency filter



Implementation of Bragg reflector into simulation

Time domain —FFT→ Frequency domain

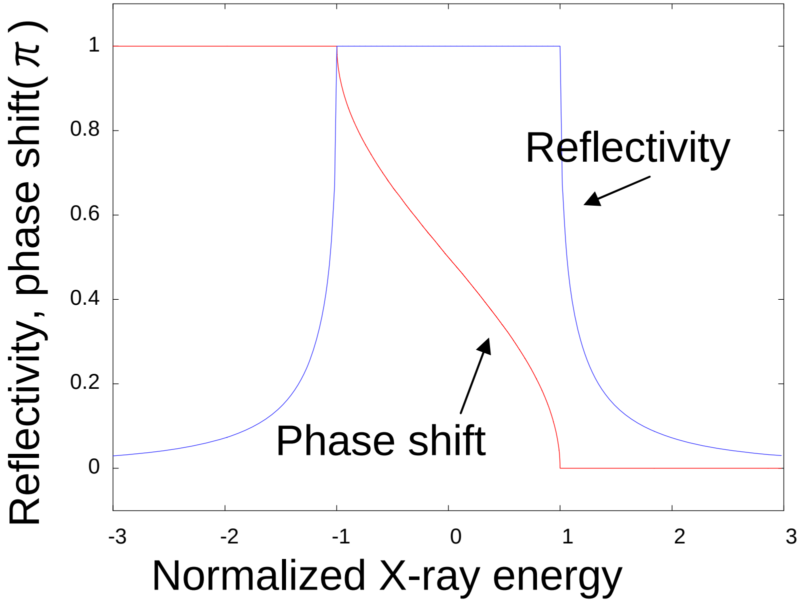
FEL interaction

Bragg reflector
Frequency filter

Time domain ←FFT— Frequency domain

Phase shift in Bragg reflection

The Darwin reflectivity curve



The amplitude reflectivity curve

$$r(x) = \left(\frac{S_0}{T_0}\right) = \begin{cases} x - \sqrt{x^2 - 1} & \text{for } x \geq 1 \\ x - i\sqrt{1 - x^2} & \text{for } -1 \leq x \leq 1 \\ x + \sqrt{x^2 - 1} & \text{for } x \leq -1 \end{cases}$$

Jens Als-Nielsen, Des McMorrow,
Elements of Modern X-ray Physics.
Wiley

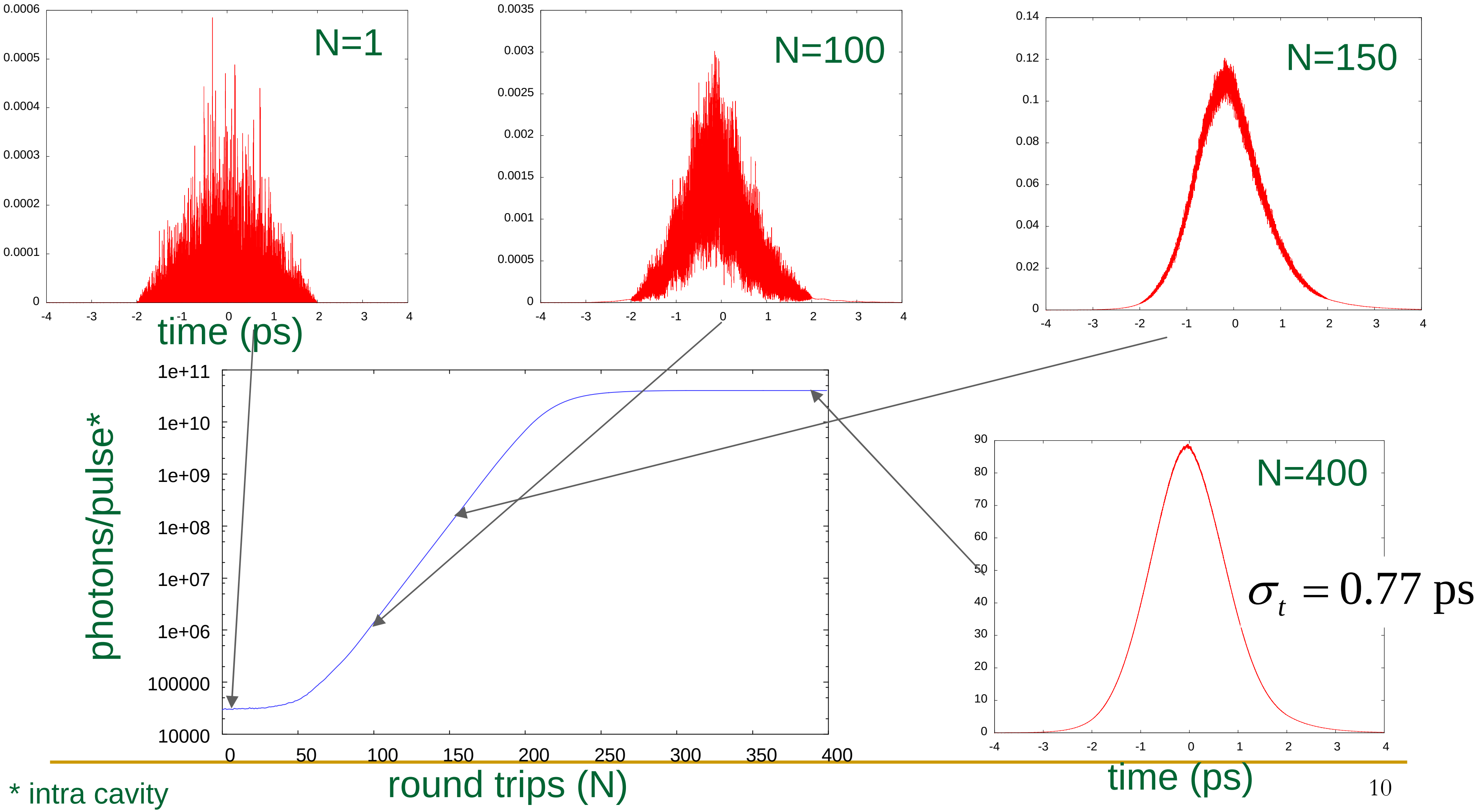
Parameters for XFELO simulation

XFELO is assumed to be implemented in a recirculation loop of ERL synchrotron radiation source.

- FEL wavelength = 0.1 nm (12 keV)
- E-beam energy = 7GeV
- The number of undulator periods =3000
  (slippage length = 300 nm)
- Triangular electron bunch with FWHM width of 2 ps
- Small signal gain = 22%
- Optical cavity loss ＝ 10%
- Cavity bandwidth ＝ 12 meV (12meV/12keV = $1\text{x}10^{-6}$)

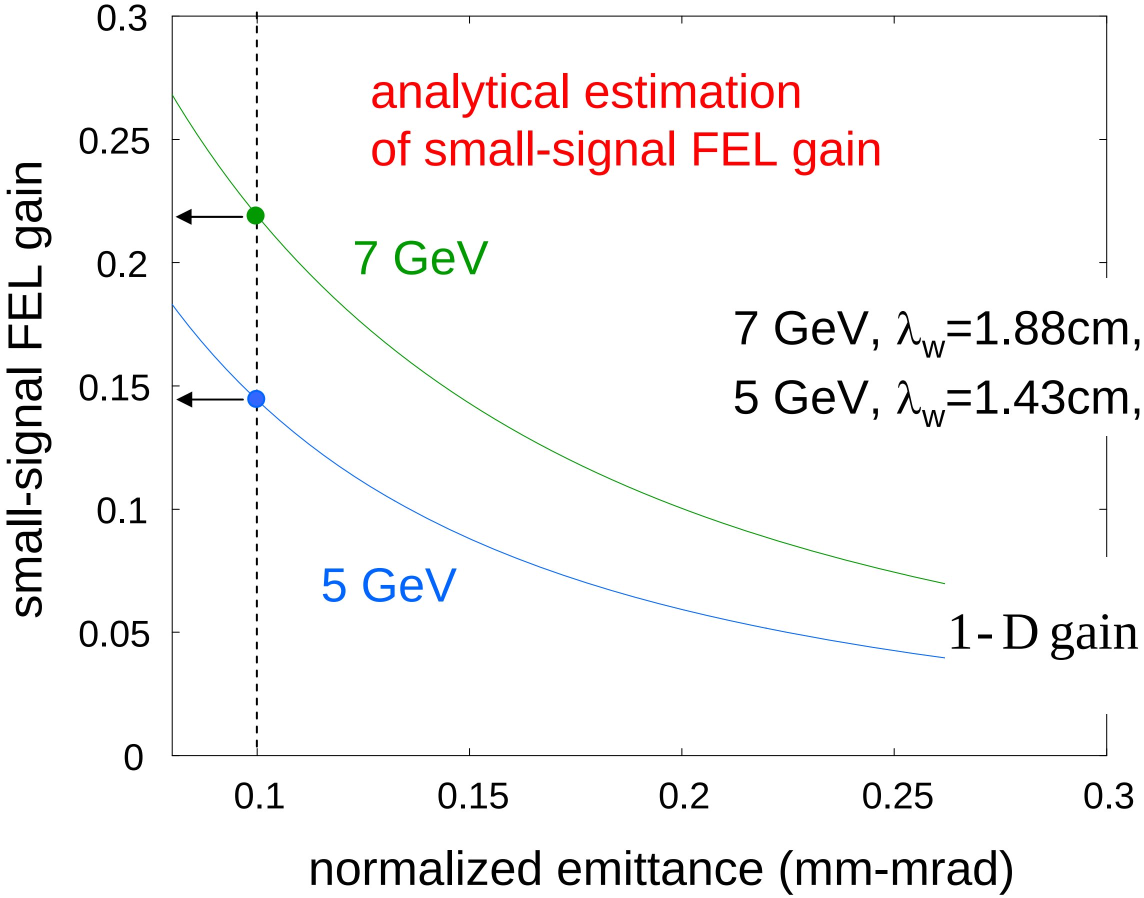
Evolution of XFEL pulse as a function of round-trips

$\delta L = -5.6 \mu m$



* intra cavity

XFELO with 5 and 7-GeV ERLs



$$\lambda = \lambda_w \frac{1+a_w^2}{2\gamma^2}$$

7 GeV, λ_w=1.88cm, gap=5mm, a_w=1 → λ=0.1nm

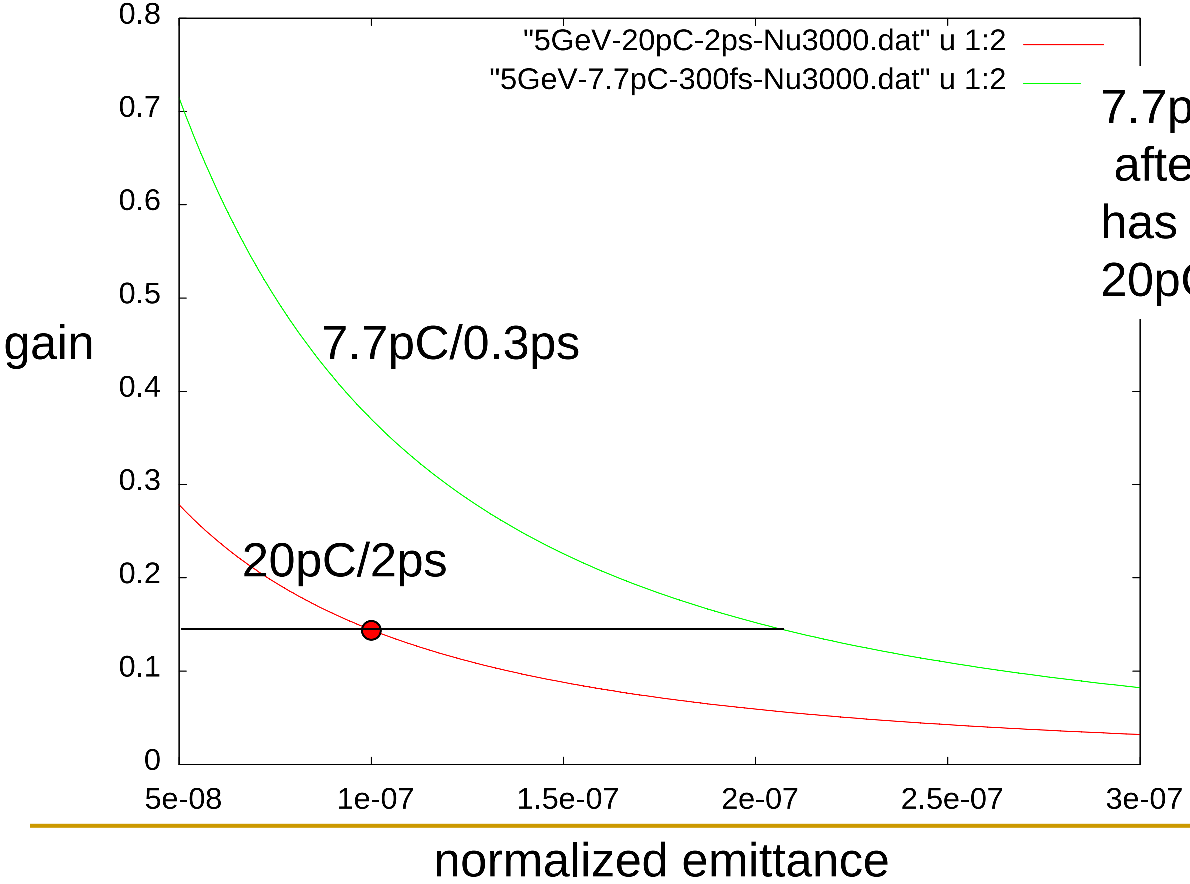
5 GeV, λ_w=1.43cm, gap=5mm, a_w=0.59 → λ=0.1nm

$$\text{1-D gain} \propto \rho^3 = \frac{1}{16\pi} a_w^2 \lambda_w^2 [JJ]^2 \frac{1}{\gamma^3} \frac{I_p}{I_A} \frac{1}{\Sigma}$$

$$\frac{\rho^3(5GeV)}{\rho^3(7GeV)} = 0.65$$

5GeV ERL XFELO feasible ?

5GeV, 40pC, 0.1mm-mrad → 28% ➡ looks very difficult



7.7pC/0.3ps with <0.2mm-mrad after bunch compression has gain higher than 20pC/2ps with 0.1 mm-mrad

⬇

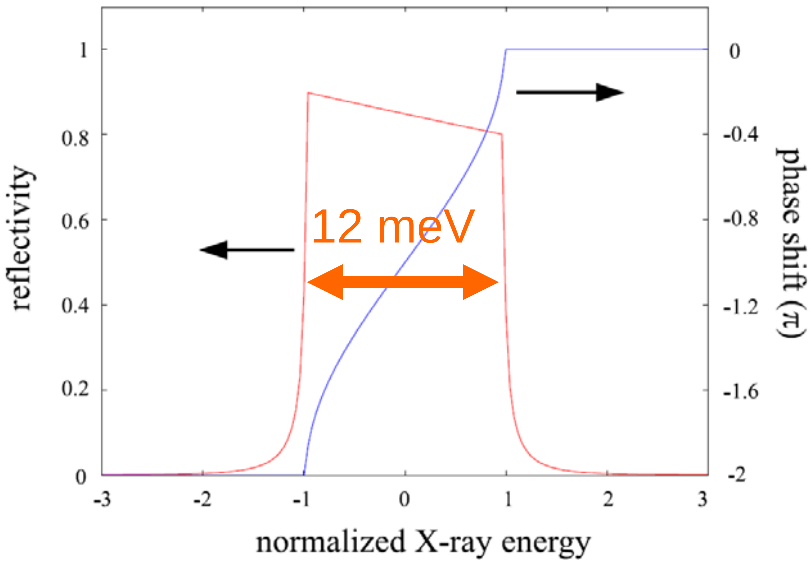
velocity bunching

Gain reduction of the bandwidth mismatch

K-J. Kim et al., PRL 100, 244802 (2008).

$$\Lambda_m = (g - \alpha)/2 - (u/2\tau_M)^2 - 0.5\sqrt{g}(2m+1)(\tau_M/\tau_{\rm el})$$

- growth rate of the *m*-th mode: Λ_m
- gain: g
- loss: α
- cavity length detuning: $(u/2\tau_M)^2$
- bandwidth mismatch: $0.5\sqrt{g}(2m+1)(\tau_M/\tau_{\rm el})$



reflectivity and phase shift for a cavity round trip

$$\sigma_\omega^M >> \sigma_\omega^{el} \quad or \quad \tau_M << \tau_{el}$$

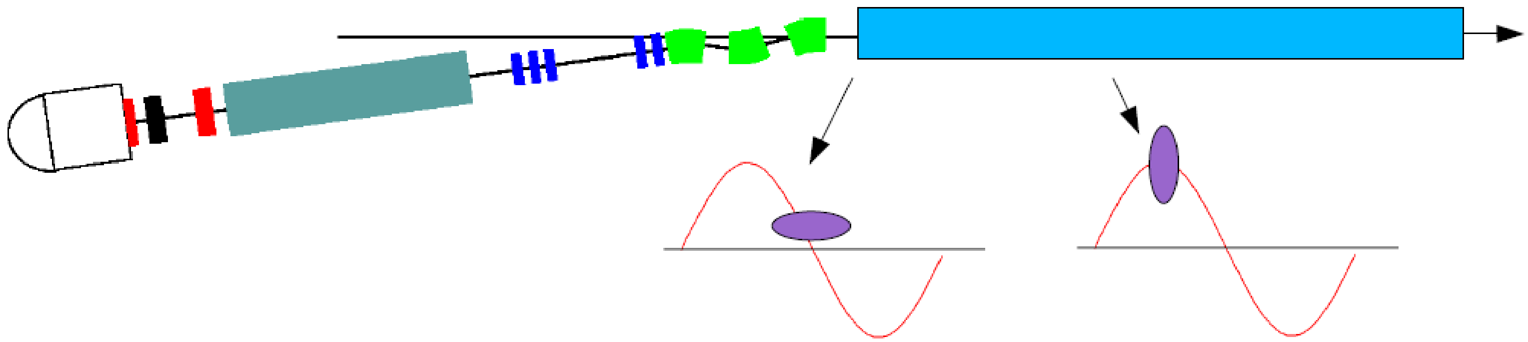
bandwidth of the Bragg mirrors = 12 meV

$$\tau_M = 100\,\text{fs}$$

$$\tau_{el} >> 100\,\text{fs}$$

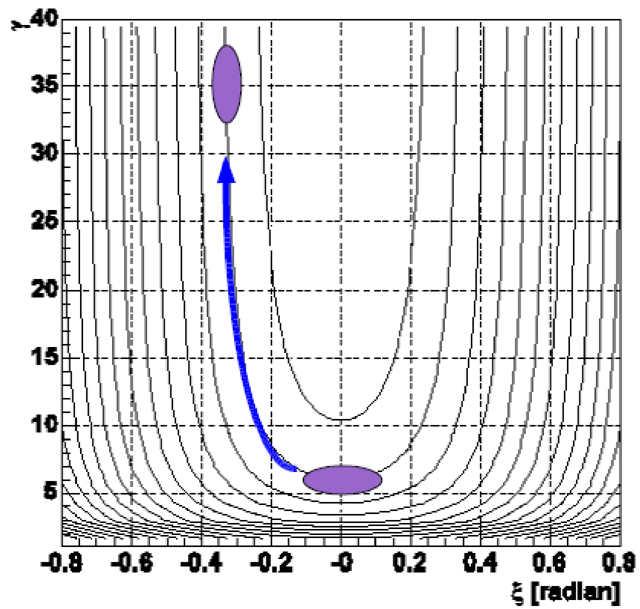
In the following calculations, we choose $\tau_{el} = 400\,\text{fs}$

Velocity bunching in a main linac

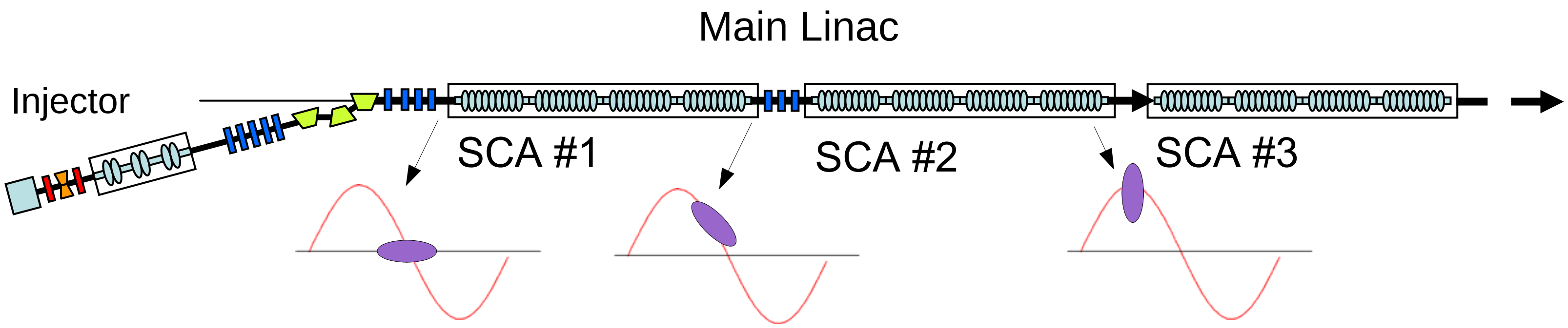


Is it possible to make velocity bunching at the beginning of main linac ?

- how short bunch ?
- merging energy ?
- emittance growth ?
- energy-recovery OK ?
- HOM loading to the main linac ?
- residual energy spread ?



Velocity bunching in an ERL main linac



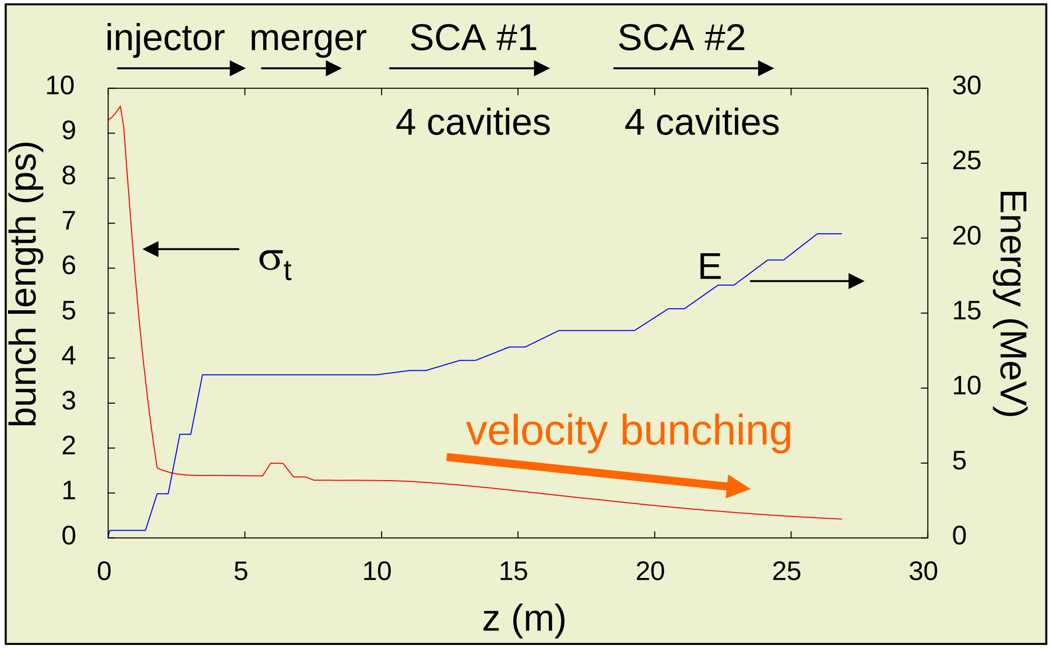
Velocity bunching for a SASE-FEL injector L. Serafini and M. Ferrario, AIP-Porc. (2001)

Velocity bunching for an ERL light source H. Iijima, R. Hajima, NIM-A557 (2006).

Velocity bunching for an X-FELO R. Hajima, N. Nishimori, FEL-2009

(1) no additional component is required
(2) only 2-3% SCAs are used for the velocity bunching
(3) residual energy spread is smaller than magnetic compression
(4) moderate emittance growth for low bunch charge

Example of the velocity bunching

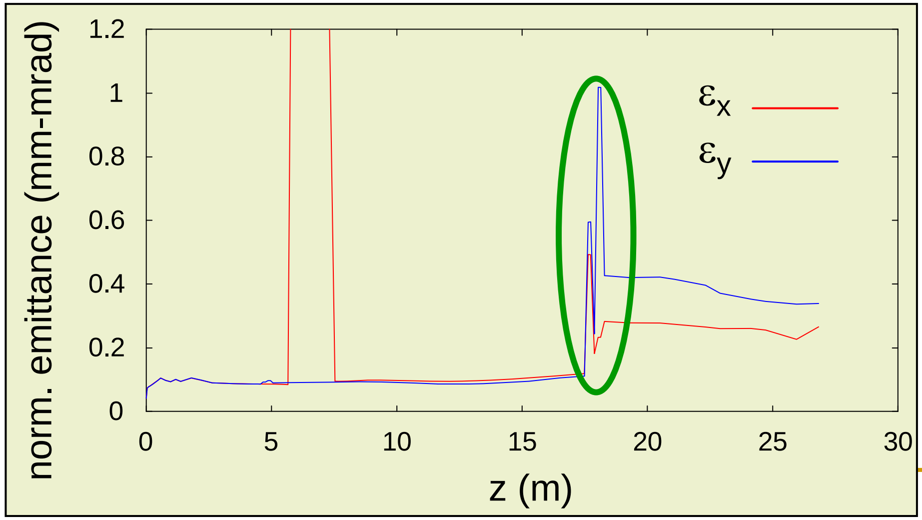


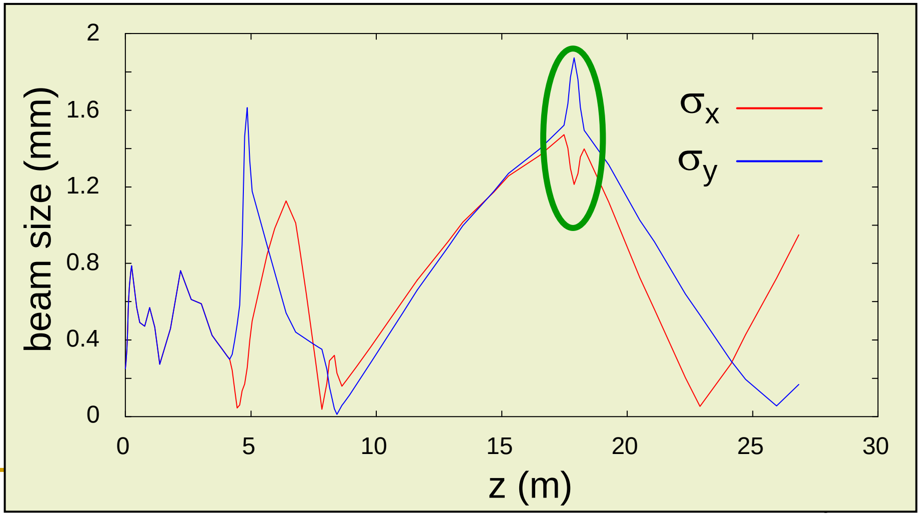
PARMELA simulation

bunch charge q = 7.7 pC

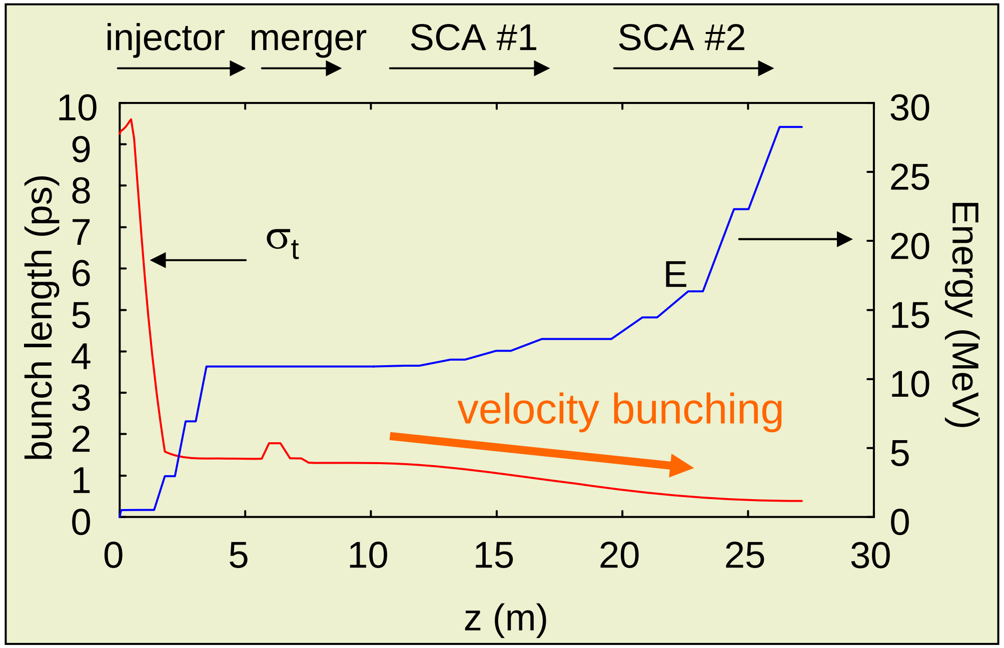
velocity bunching
bunching in 8 cavities
injection 10.9 MeV, 1.3 ps, -85 deg.
gradient E_{acc} = 8.5 MV/m

emittance growth by chromatic aberration





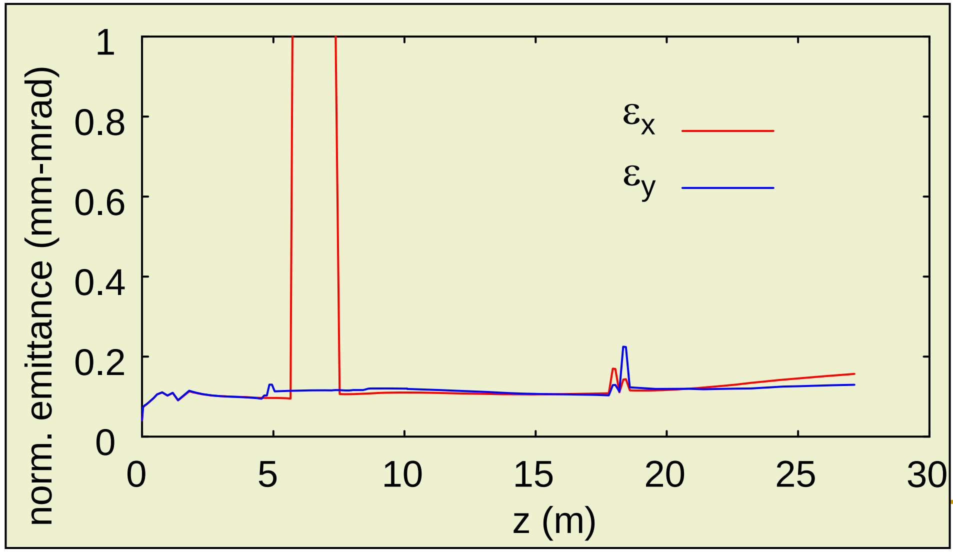
Optimum design of the velocity bunching

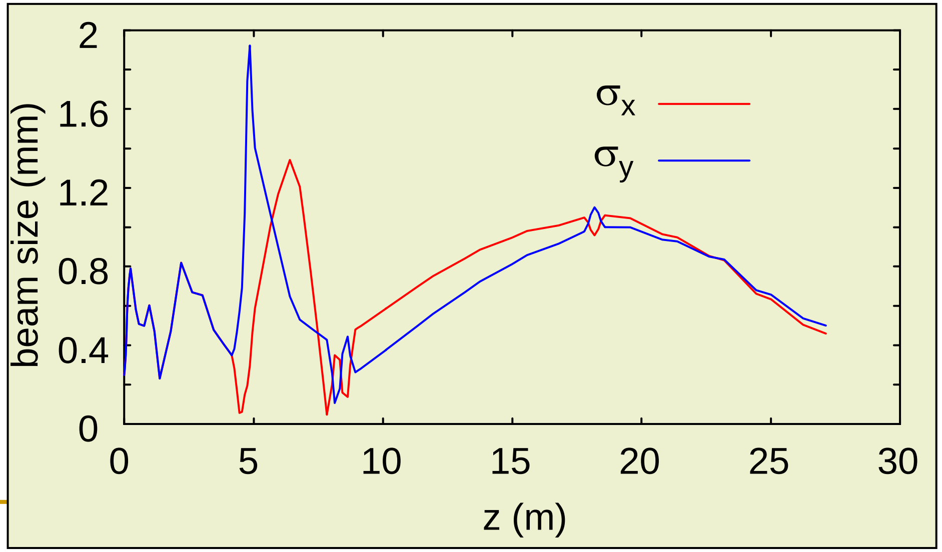


bunch charge   q = 7.7 pC

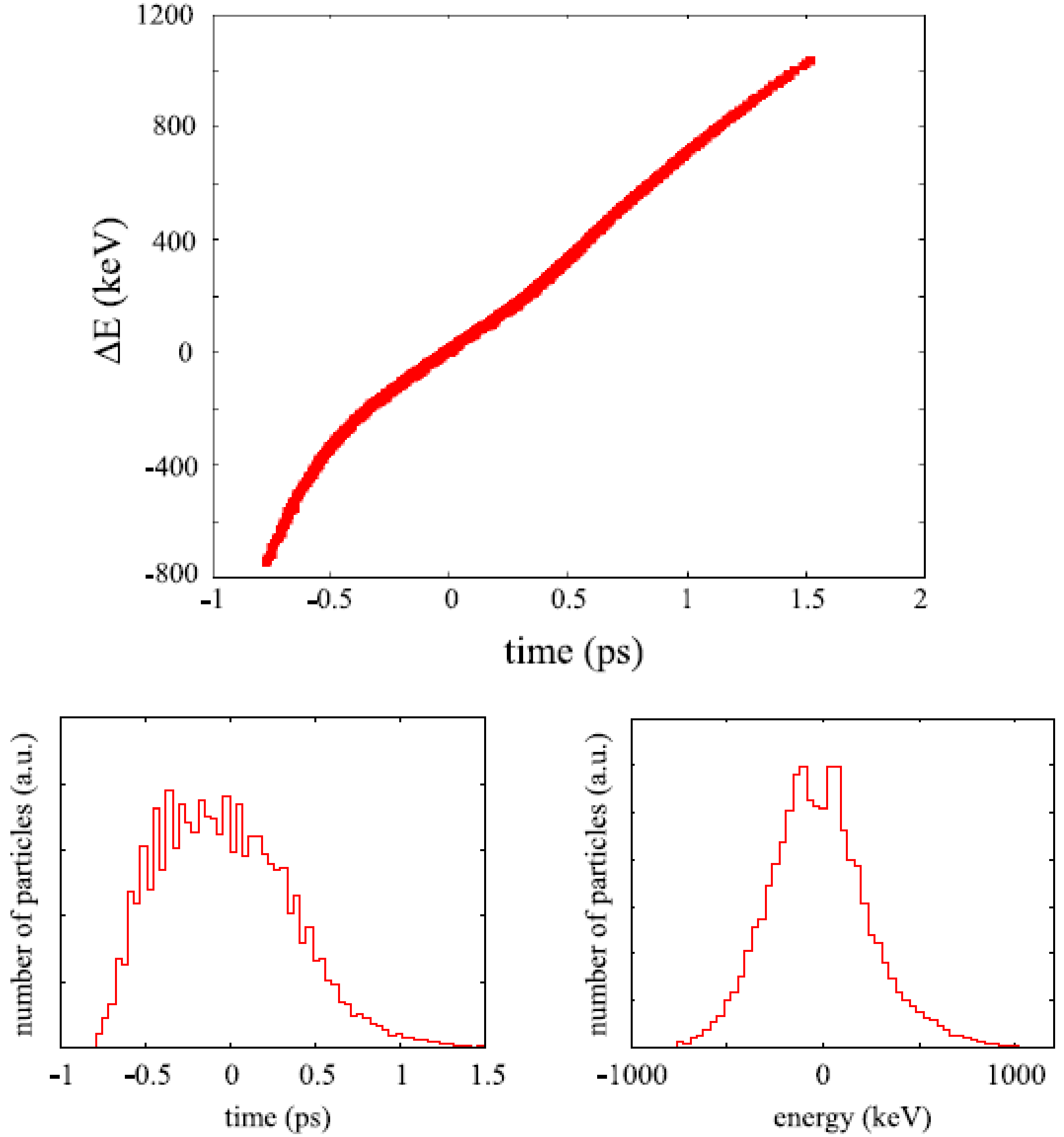
velocity bunching
bunching in 6 cav. + on-crest 2 cav.
injection 10.9 MeV, 1.3 ps, -90 deg.
gradient E_{acc} = 8.5 MV/m

at the SCA#2 exit
E = 27.7 MeV, σ_t = 380 fs, σ_E = 250 keV
ε_x = 0.16 mm-mrad, ε_y = 0.13 mm-mrad

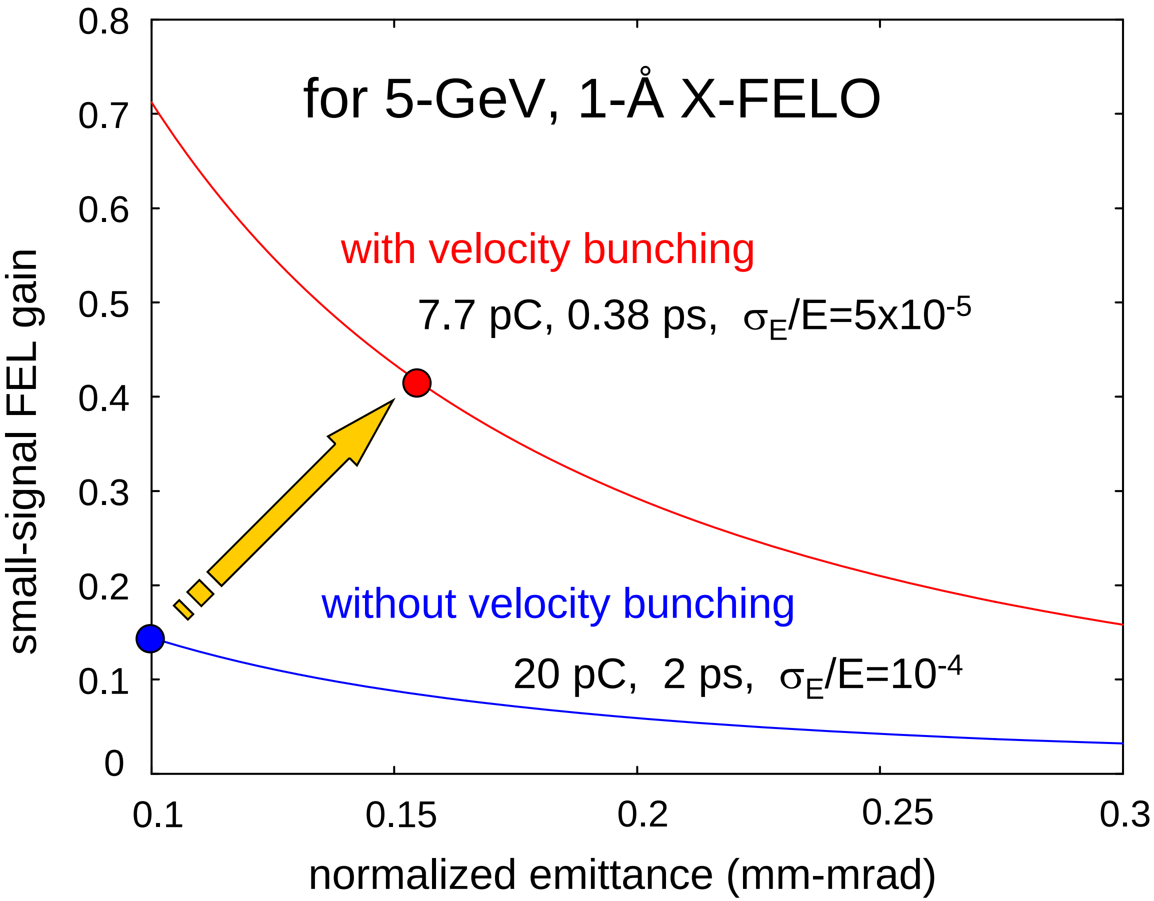




Longitudinal phase plot at the SCA #2 exit



Enhancement of the FEL gain by velocity bunching

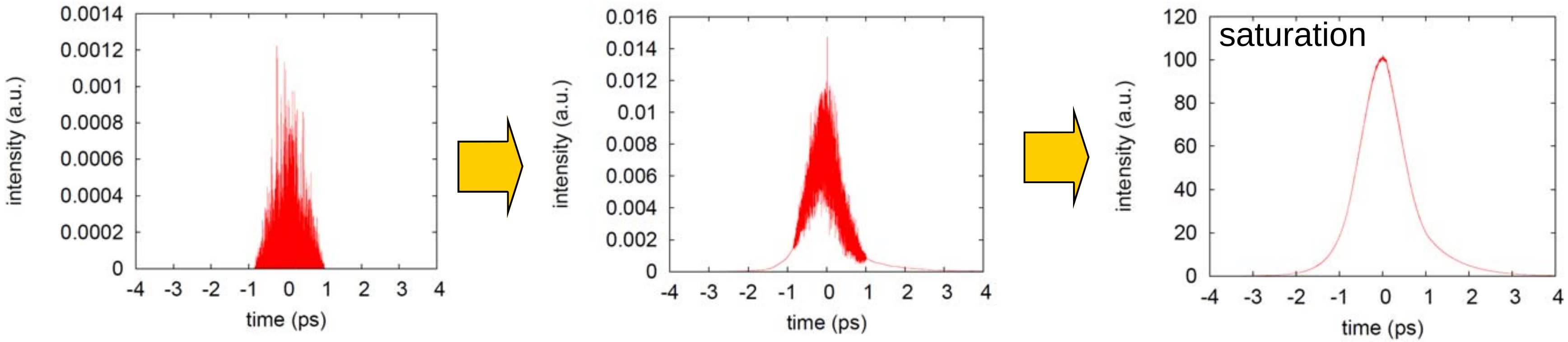


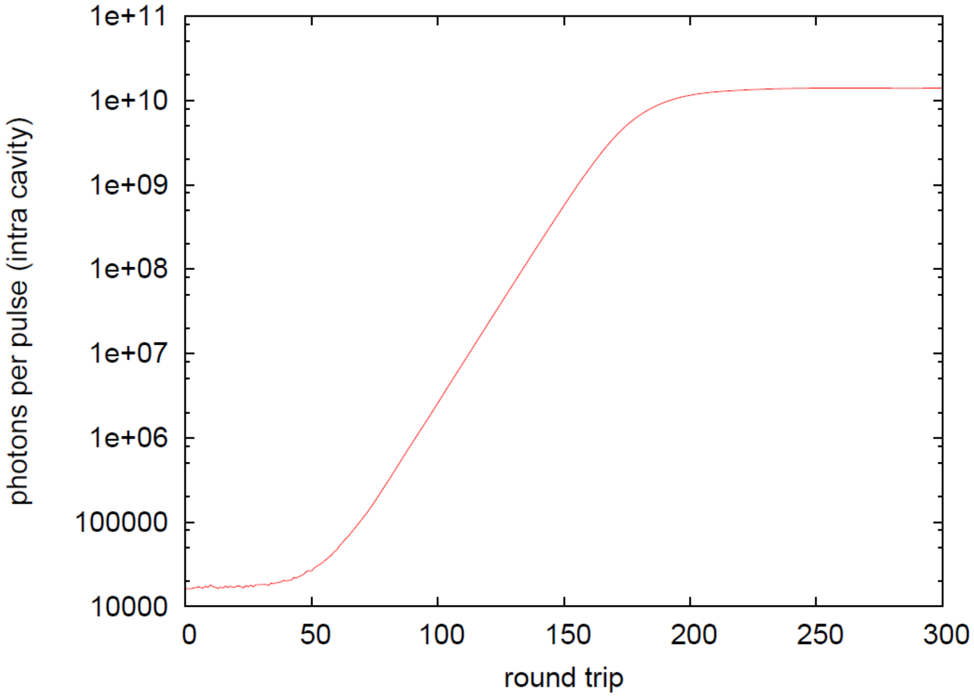
1Å X-FELO

Energy	5 GeV	→
charge	20 pC	7.7pC
σ_t	2 ps	0.38 ps
σ_E/E	1e-4	5e-5
a_w	0.59	→
λ_u	1.43 cm	→
N_u	3000	→
$\beta^*=Z_R$	10 m	→
ε_n	0.1mm-mrad	0.16mm-mrad
gain	14 %	40 %

Significant enhancement of the FEL gain by velocity bunching.
Gain~40% is possible even with emittance growth during the bunching.

Simulation of XFELO (5 GeV with velocity bunching)





After the saturation:

pulse duration

τ=1.2 ps (FWHM)

photons/pulse (intra cavity)

N_p = 2×10^{10}

photons/pulse (extracted)

N_p = 7×10^{8}

Summary

- Gain of XFELO can be increased by velocity bunching in an ERL main linac.
- Both the higher peak current and the smaller energy spread contribute to the gain enhancement.
- For 1-Å XFELO at 5-GeV, Gain~40% is feasible. → better margin for the X-ray resonator