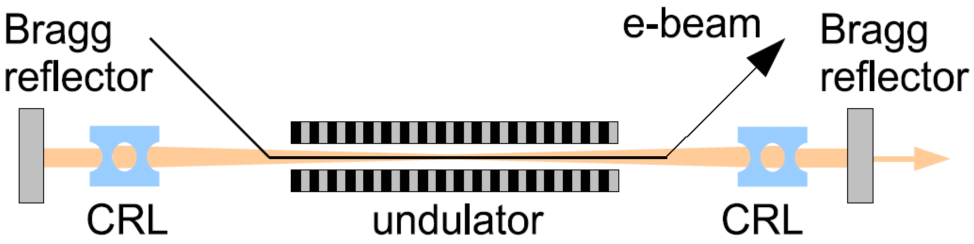
Velocity bunching for an X-FELO at 5 GeV (presented at FEL-09, WEPC34)

R. Hajima (JAEA)

Sep. 1, 2009

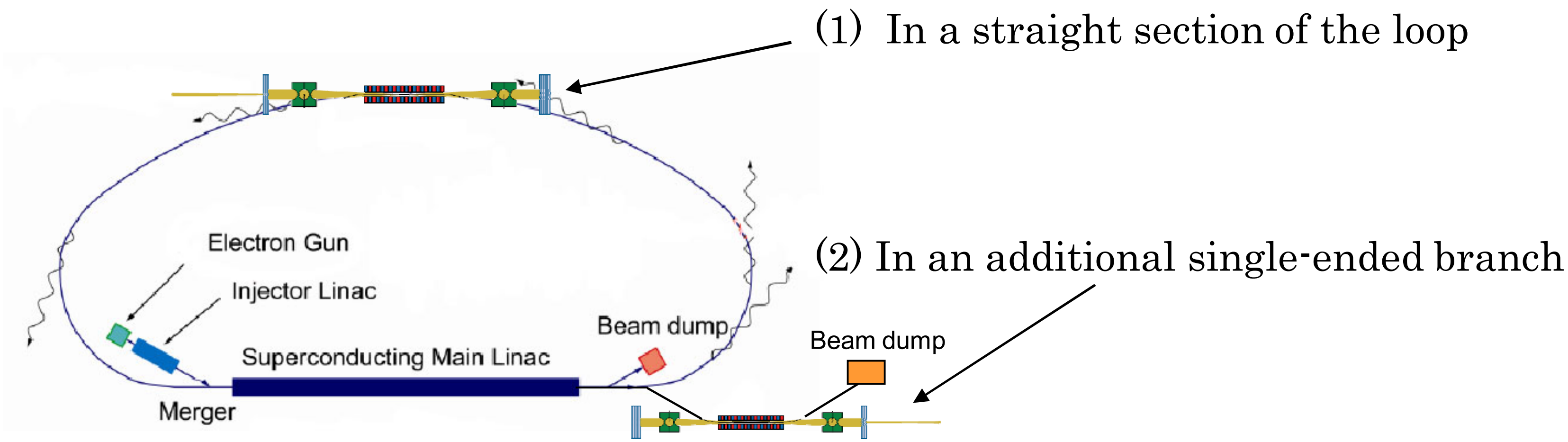
ERL Beam Dynamics WG.

X-ray FEL Oscillator = X-FELO

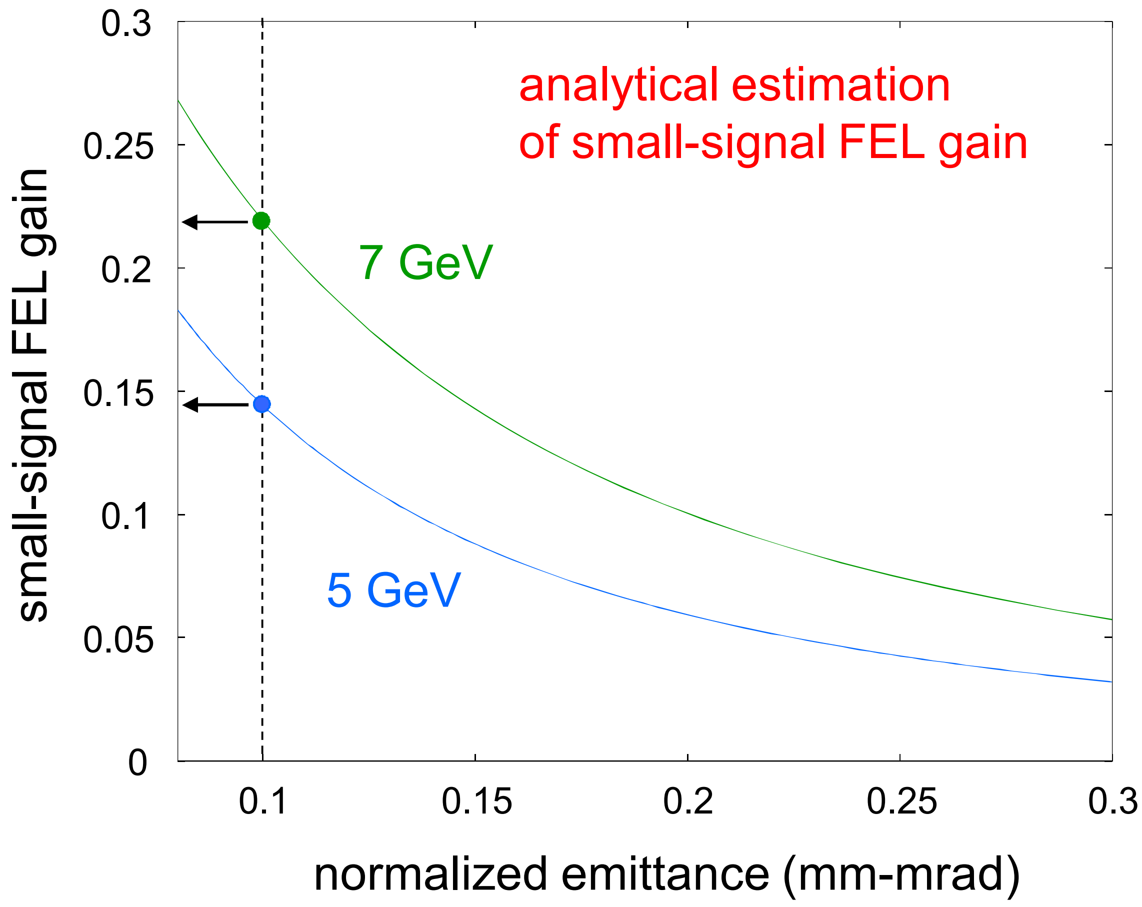


K-J. Kim et al., PRL 100, 244802 (2008).

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



X-FELO with 5 and 7-GeV ERLs



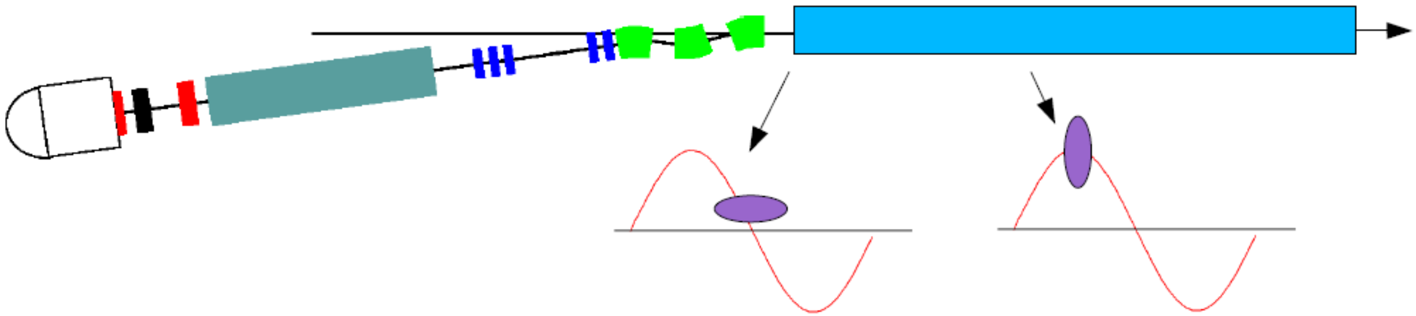
1 A X-FELO

Energy	5 GeV	7 GeV
charge	20 pC	→
st	2 ps	→
sE/E	1e-4	→
aw	0.59	1.0
lu	1.43 cm	1.88 cm
Nu	3000	→
b*=ZR	10 m	→
en	0.1 mm-mrad	→
gain	14 %	22 %

Proposal of velocity bunching at ERL-05

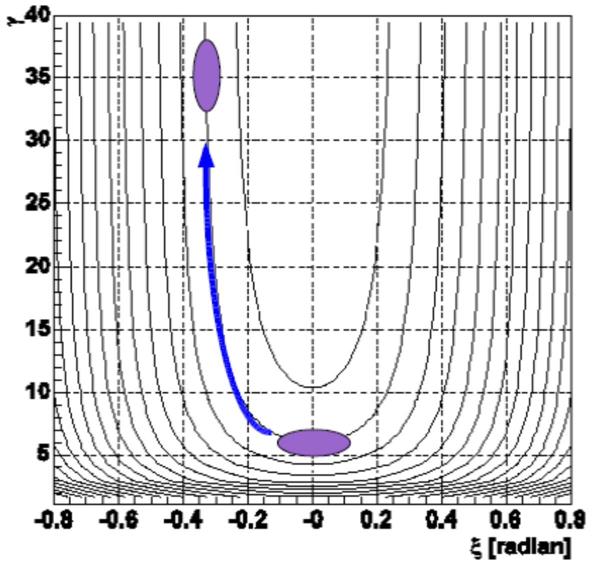
Velocity bunching in a main linac

ERL 2005

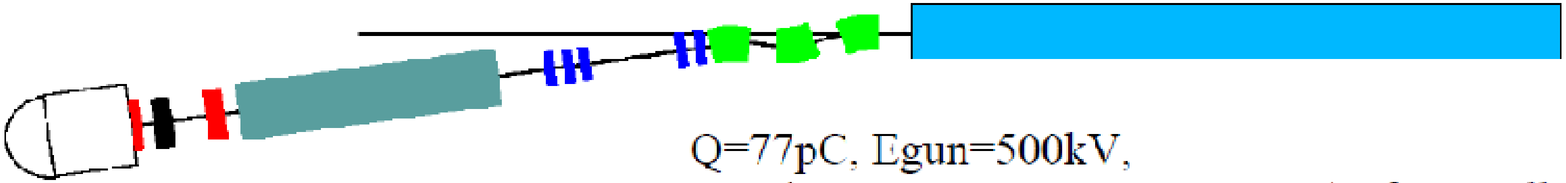


Is it possible to make velocity bunching at the beginning of main linac ?

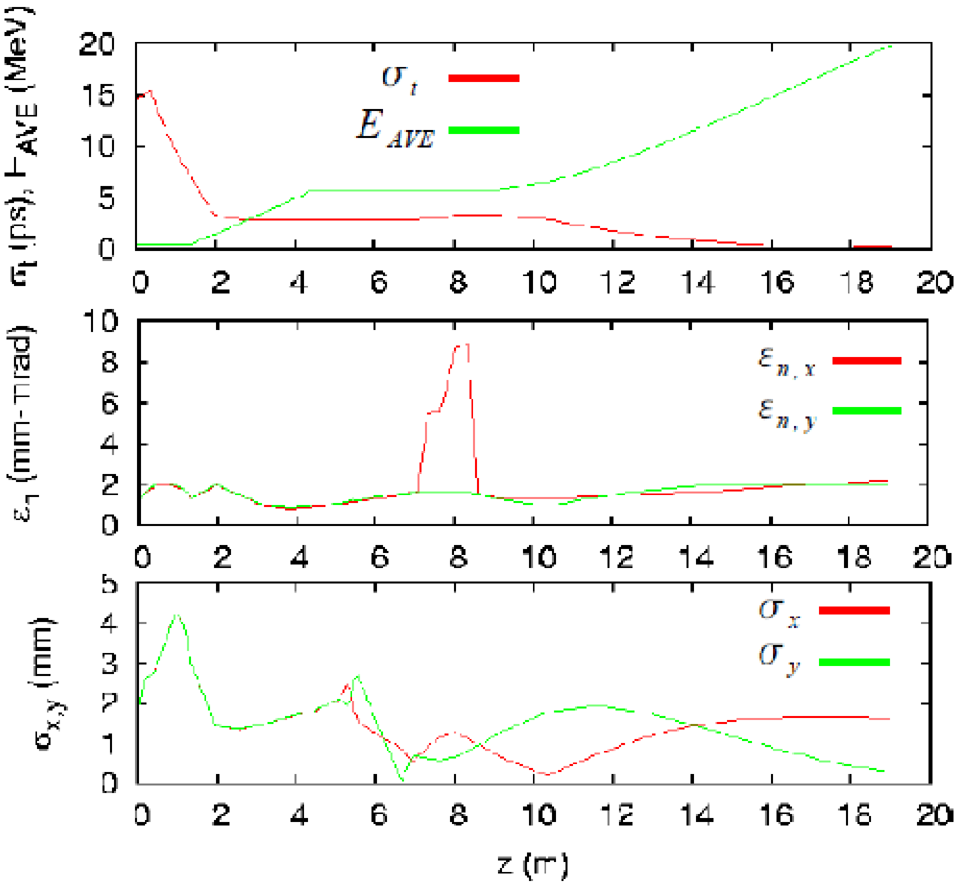
- how short bunch ?
- merging energy ?
- emittance growth ?
- energy-recovery OK ?
- HOM loading to the main linac ?
- residual energy spread ?



PARMELA simulation from a gun



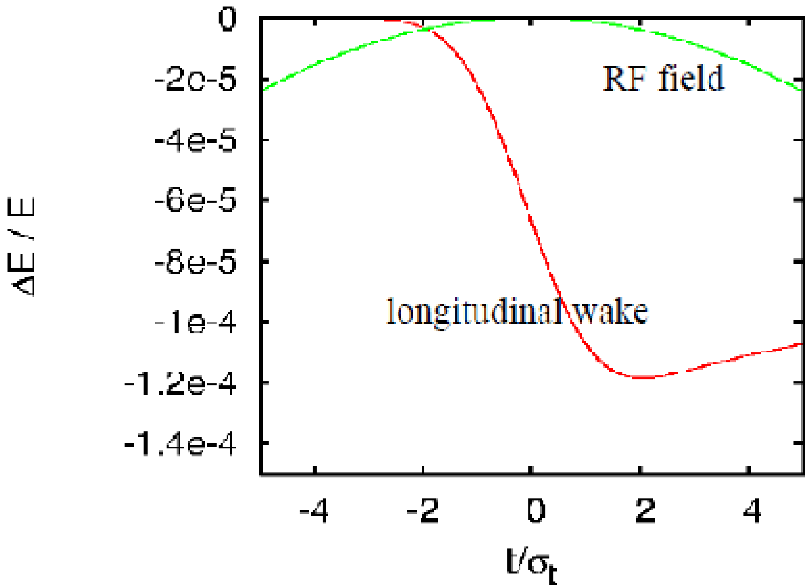
Q=77pC, Egun=500kV,
merging at 5.8MeV, Eacc=8.2MV/m for 9-cell



σ_t = 15 ps (gun) → 3.2 ps (merger)
→ 170 fs (after 9-cell x 8)

$\varepsilon_{n,x}$ = 2.2 mm-mrad
$\varepsilon_{n,y}$ = 1.9 mm-mrad

Energy Spread



correlated energy spread by longitudinal wake and RF curvature.

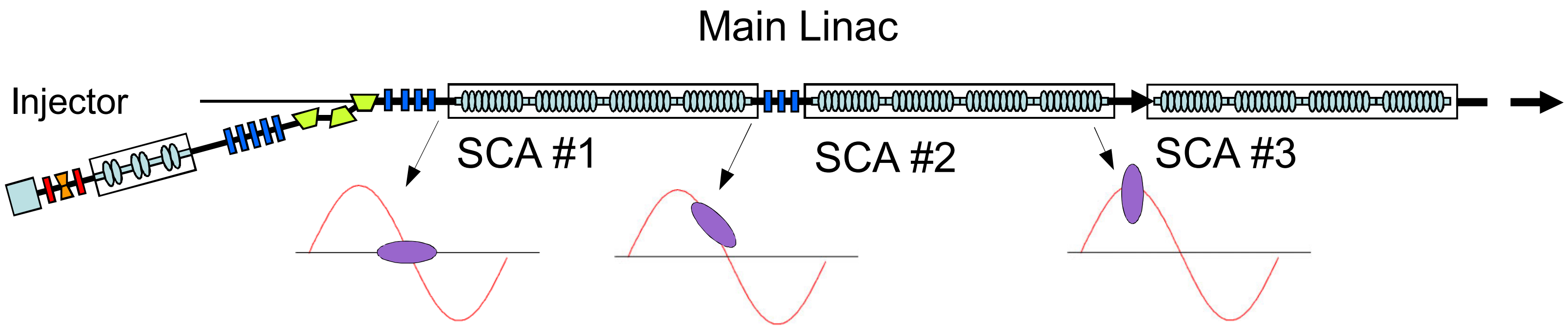
we assume a Gaussian bunch σ_t = 170 fs, Q=77 pC, TESLA cavity.

energy spread introduced by velocity bunching :

$\sigma_E/E \sim 1.1 \times 10^{-4}$ (final energy 6 GeV)

cf. $\sigma_E/E \sim 3.4 \times 10^{-3}$ for BC in a half-arc.

Velocity bunching in an ERL main linac



Velocity bunching in an ERL main linac was originally proposed for ultrafast X-ray pulses from undulator radiation [1].
It is also useful for the operation of an X-FELO for the following reasons:

(1) no additional component is required
(2) first 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

[1] H. Iijima, R. Hajima, NIM-A557 (2006).

Gain reduction of the bandwidth mismatch

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

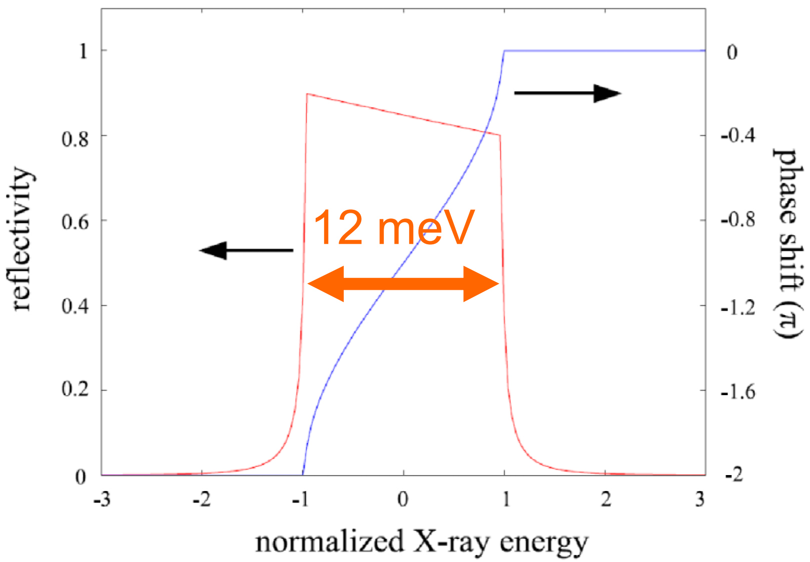
growth rate of the *m*-th mode

gain

loss

cavity length detuning

bandwidth mismatch



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

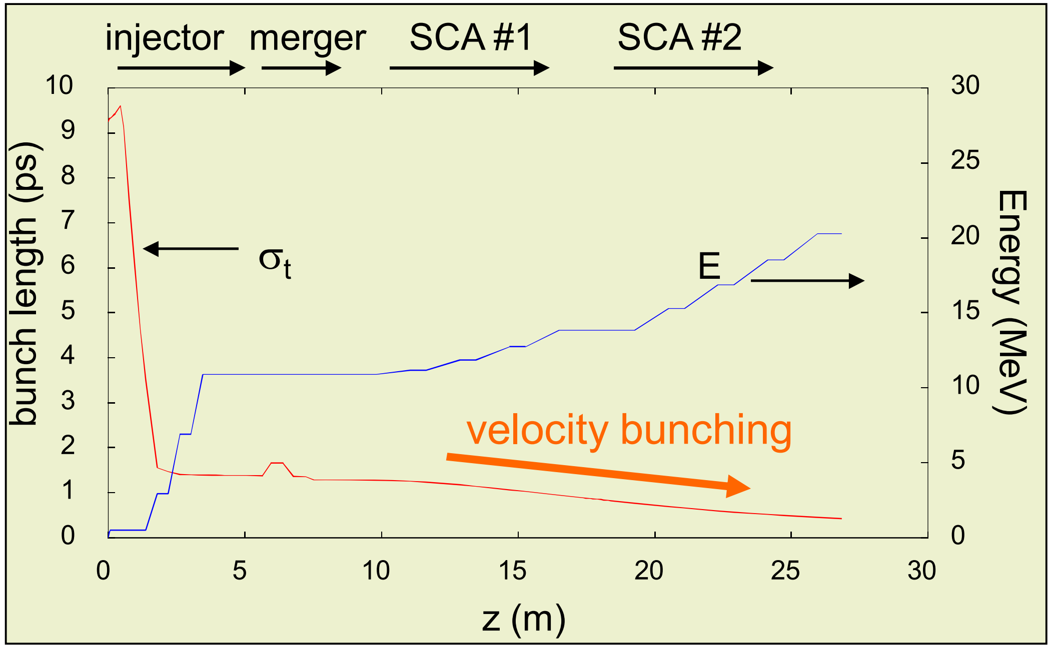
bandwidth of the Bragg mirrors = 12 meV

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

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

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

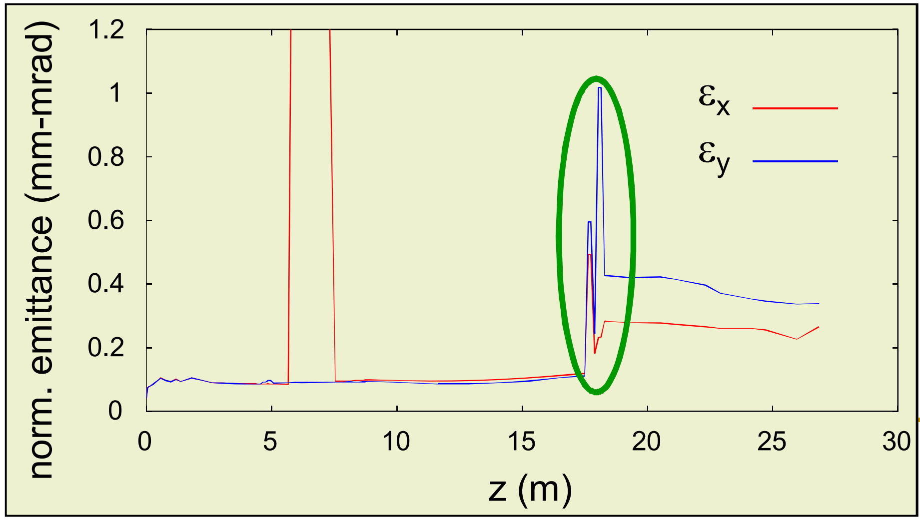
Example of the velocity bunching

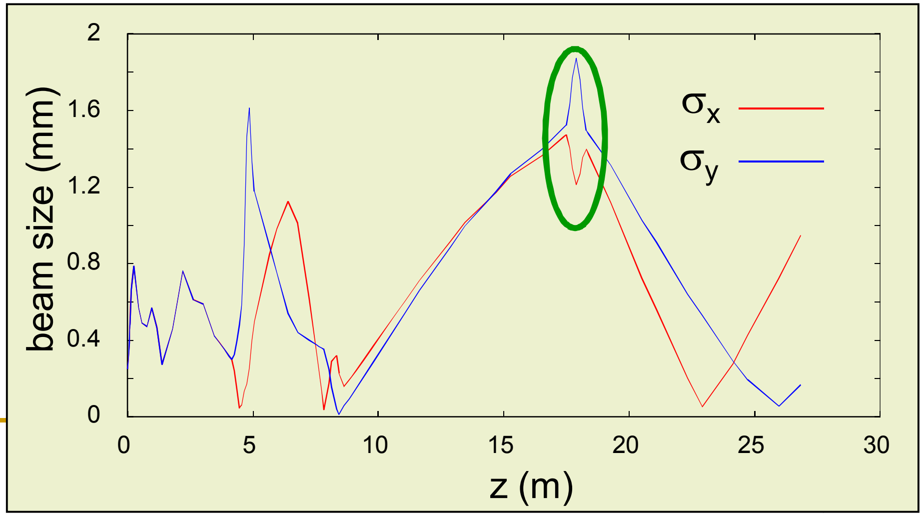


bunch charge q = 7.7 pC

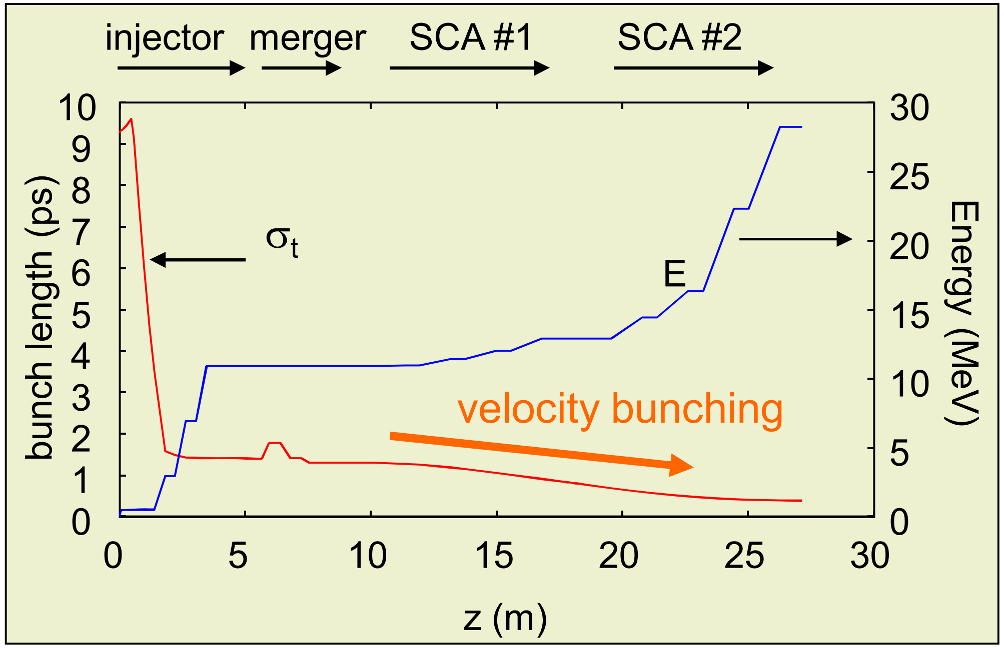
velocity bunching
bunching in 8 cavities
injection 10.9 MeV, 1.3 ps, -85 deg.
gradient E_{acc} = 8.5 MV/m

emittance growth by chromatic aberration





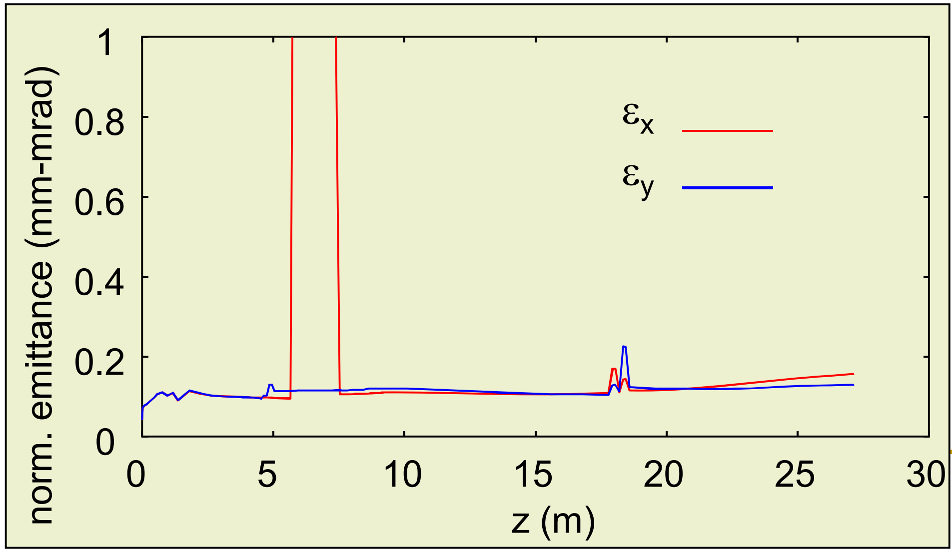
Optimum design of the velocity bunching

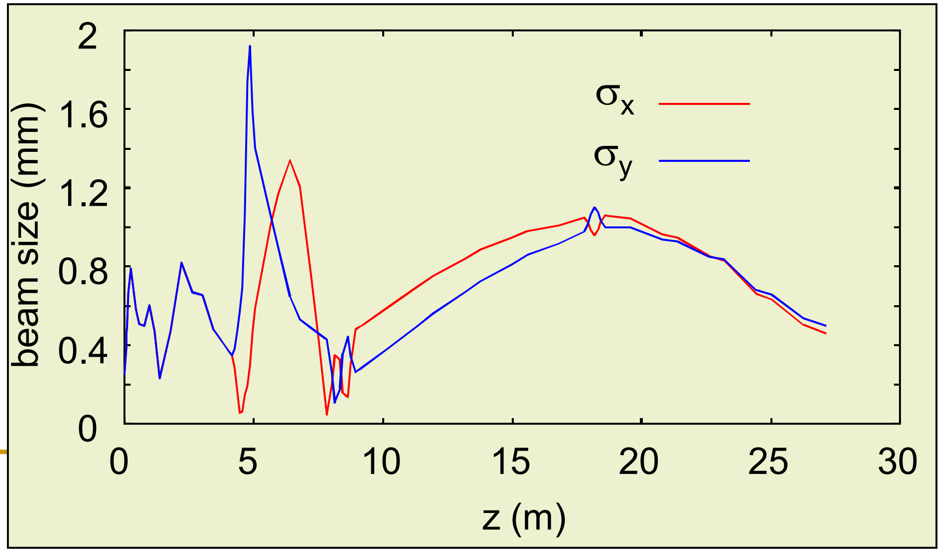


bunch charge q = 7.7 pC

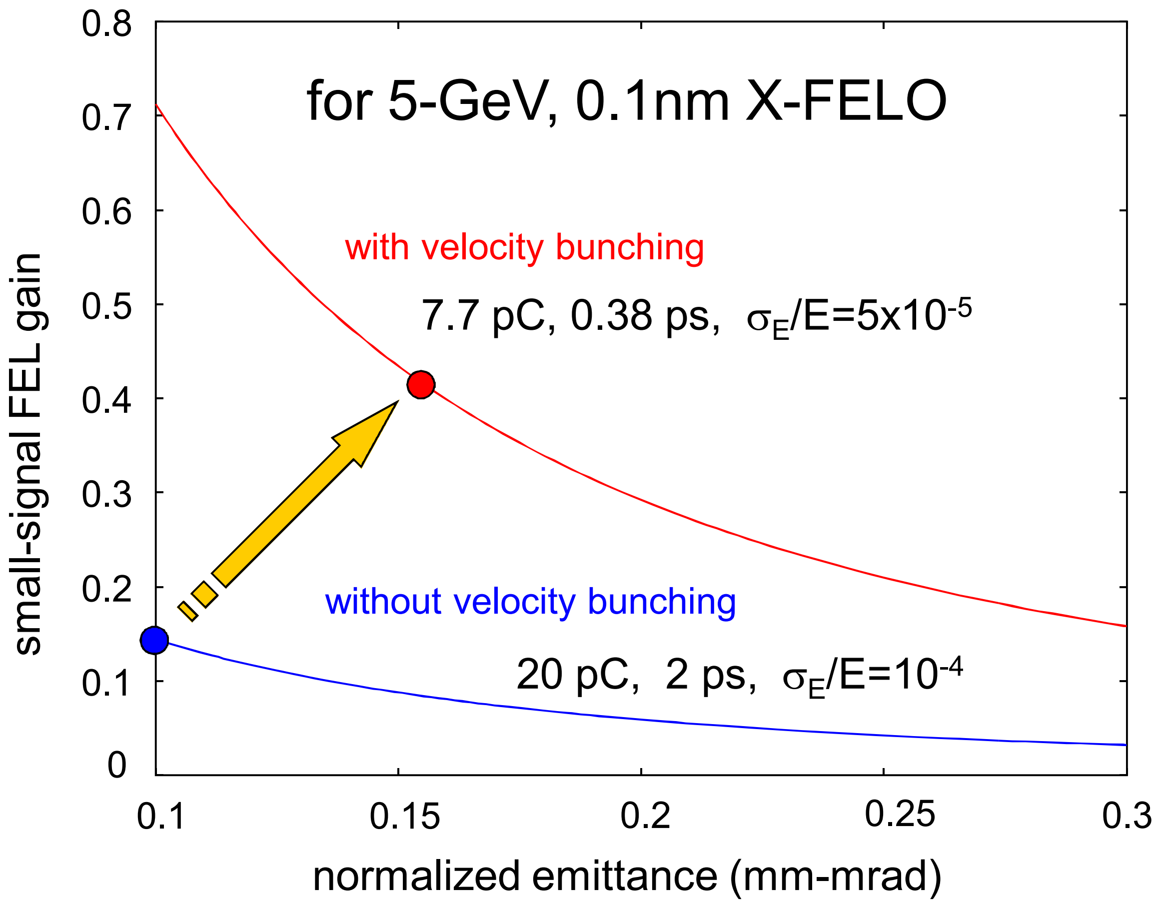
velocity bunching
bunching in 6 cav. + on-crest 2 cav.
injection 10.9 MeV, 1.3 ps, -90 deg.
gradient E_{acc} = 8.5 MV/m

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



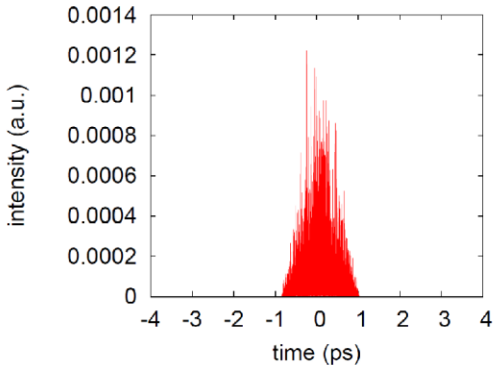


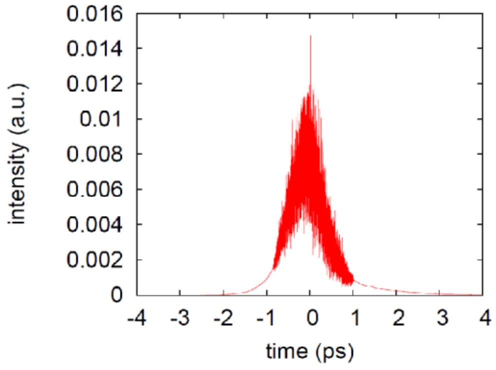
Enhancement of the FEL gain by velocity bunching

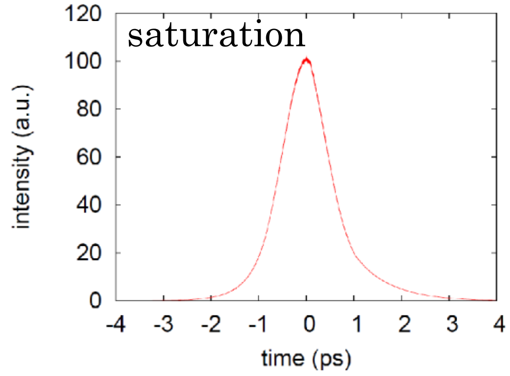


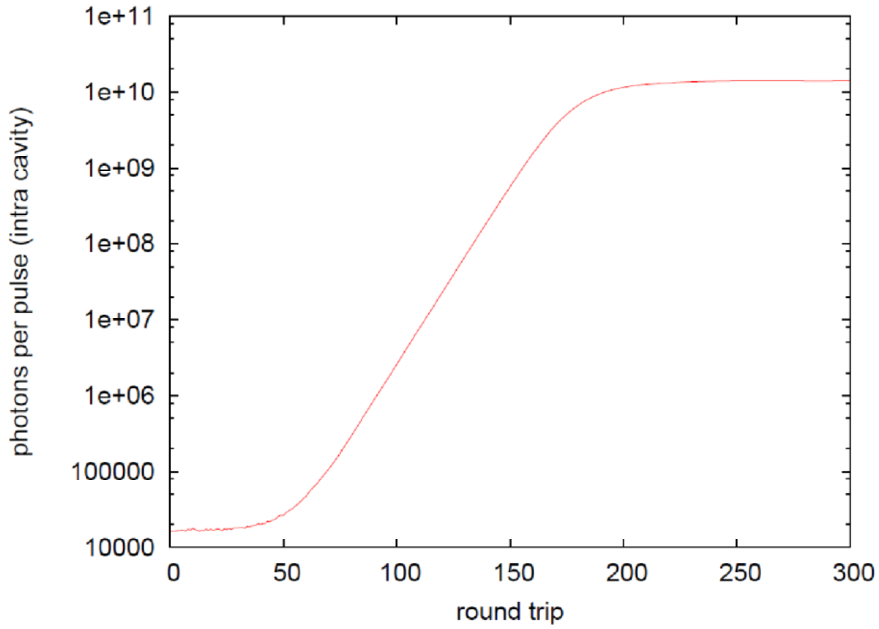
Significant enhancement of the FEL gain by velocity bunching.
gain~40% is possible even with emittance growth during the bunching.

Simulation of X-FELO









After the saturation:

photons/pulse (intra cavity)
    Np (intra) = 2×10^{10}
photons/pulse (extracted)
    Np (extra) = 7×10^{8}
pulse duration
    τ=1.2 ps (FWHM)

Summary

- Gain of X-FELO can be increased by velocity bunching in the main linac.
- Both the larger peak current and the smaller energy spread contribute to the gain enhancement.
- For 1-Å X-FELO at 5-GeV, Gain~40% is possible. → margin for the X-ray resonator
- Energy stability ~5×10^{-5} may be challenging for LLRF.