XFEL Oscillator in ERLs

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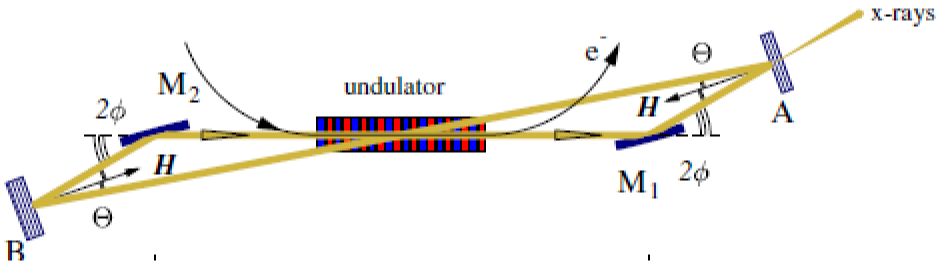
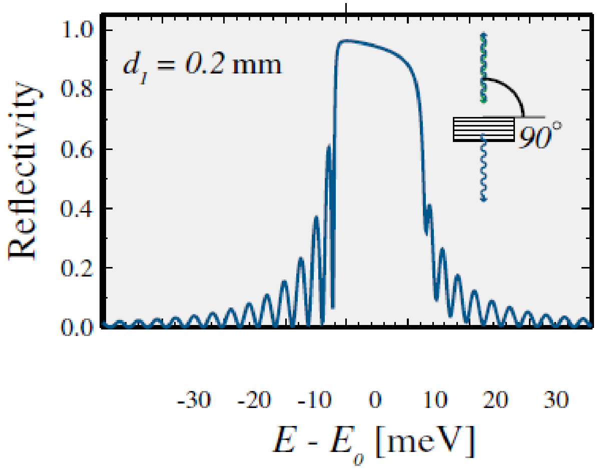
X-ray FEL Oscillator





K-J. Kim et al., PRL (2008), PRST-AB (2009)

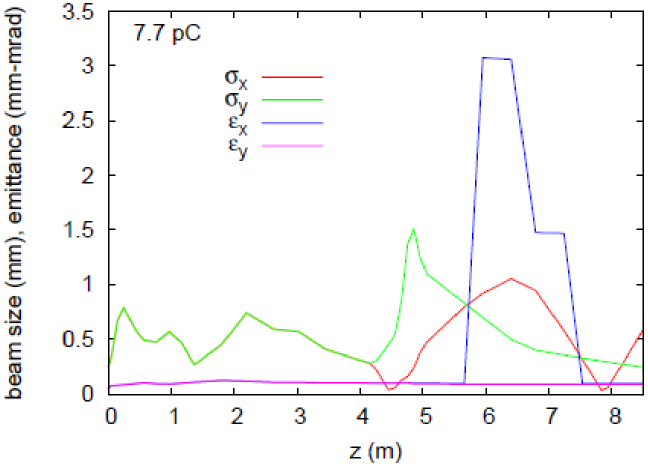
Typical electron beam parameters for XFELO

λ_1 (Å)	E (GeV)	Q (pC)	K	λ_U (cm)	N_U	Z_R (m)	g_{th} (%)	g_{sim} (%)	r (%)	P_{sat} (MW)
1	7	19	1.414	1.88	3000	10	26	28	90	19
1	7	40	1.414	1.88	3000	12	55	66	83	21
0.84	7.55	19	1.414	1.88	3000	12	26	28	90	20
0.84	10	19	2	2.2	2800	10	42	45	83	18

Energy, charge, emittance, repetition are similar to ERL beams.

ERL Injector Performance

design example

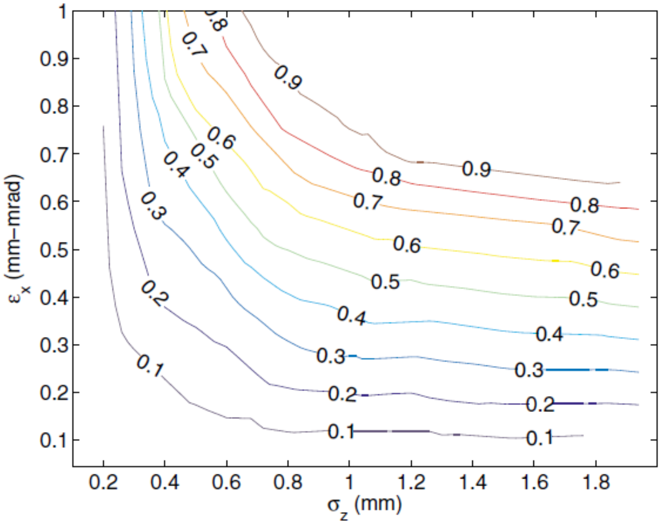


8 pC, 0.1 mm-mrad will be feasibly obtained.

500-kV DC gun, 3-D pulse shaping, and 10-MeV SCA.

R. Hajima et al.
Compact ERL CDR (2008)

Ultimate Injector

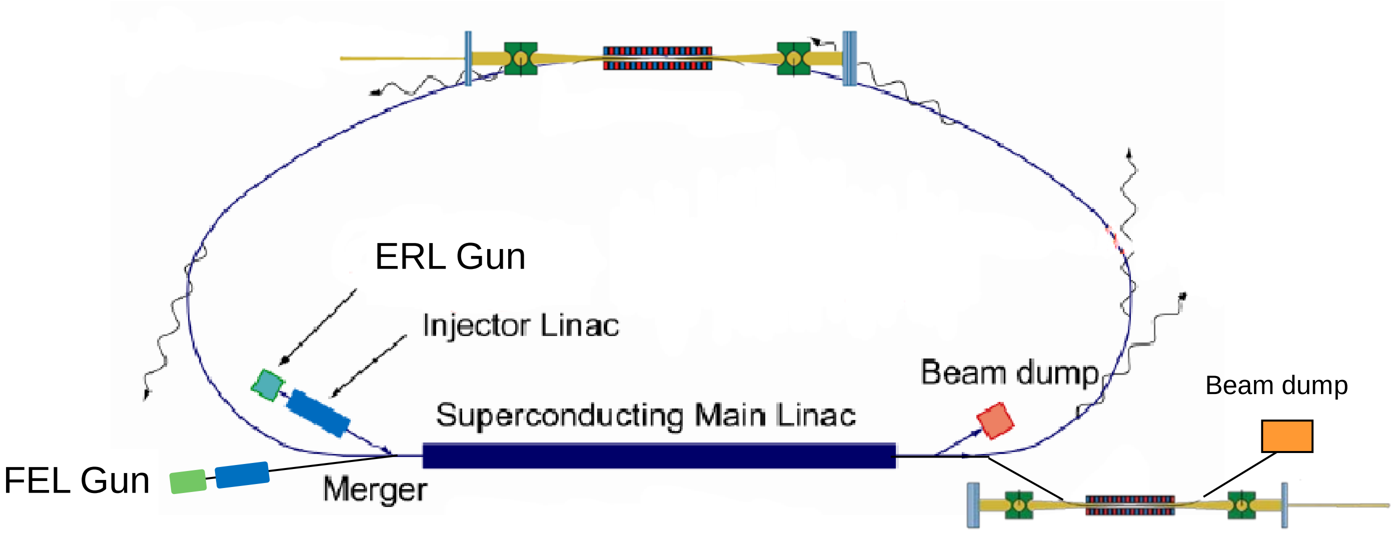


80 pC, 0.1 mm-mrad will be obtained.

750-kV DC gun, 3-D pulse shaping, and 10-MeV SCA.

I.V. Bazarov et al., PRST-AB (2005)

Integration of XFELO and ERL



Location

- straight section of the loop
- additional branch

Operation mode

- independent
- concurrent

Injector

- share an ERL injector
- use a FEL injector

From the ERL side,

XFELO adds a new feature with minor modification
ERL and XFELO provides complimentary X-rays

Growth of emittance and energy spread in a loop

E=5 GeV, ρ=25m, “half arc” = TBA x 15

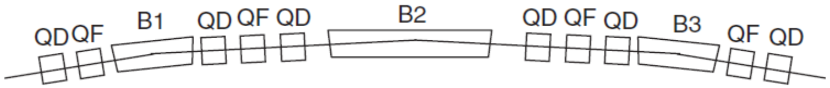


Fig. 6. A triple bend achromatic cell: $\rho = 25\,\mathrm{m}$, $\theta = 3 + 6 + 3 = 12°$.

incoherent SR

$$I_5 = 2.3\times 10^{-5}(m^{-1})$$

$$\Delta\varepsilon_x = \frac{2r_e}{3} C_q \gamma^5 I_5 = 1.4\,\mathrm{pm}$$

$$I_3 = 5.0\times 10^{-3}(m^{-2})$$

$$\Delta\left(\frac{\sigma_p}{p}\right) = \left(\frac{2r_e C_q \gamma^5 I_3}{3}\right)^{1/2} = 1.8\times 10^{-5}$$

coherent SR

$\sigma_E^{CSR} = 8\,\mathrm{keV}$ for 20pC/2ps

tuning of cell-to-cell phase advance
→ negligible emittance growth

FEL gain is preserved

energy spread after FEL lasing

$$\frac{\Delta E}{E} = \frac{1}{N_u} \sim 0.05\%$$

Energy recovery is preserved

XFELO lasing at 5-GeV?

0.1nm XFELO with a 5-mm gap Halbach-type undulator

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

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

$$JJ = J_0(\xi) - J_1(\xi), \quad \xi = \frac{a_w^2}{2(1+a_w^2)} \qquad I_A = 17\text{kA}, \ I_p = \text{peak current}, \ \Sigma = \text{mode area}$$

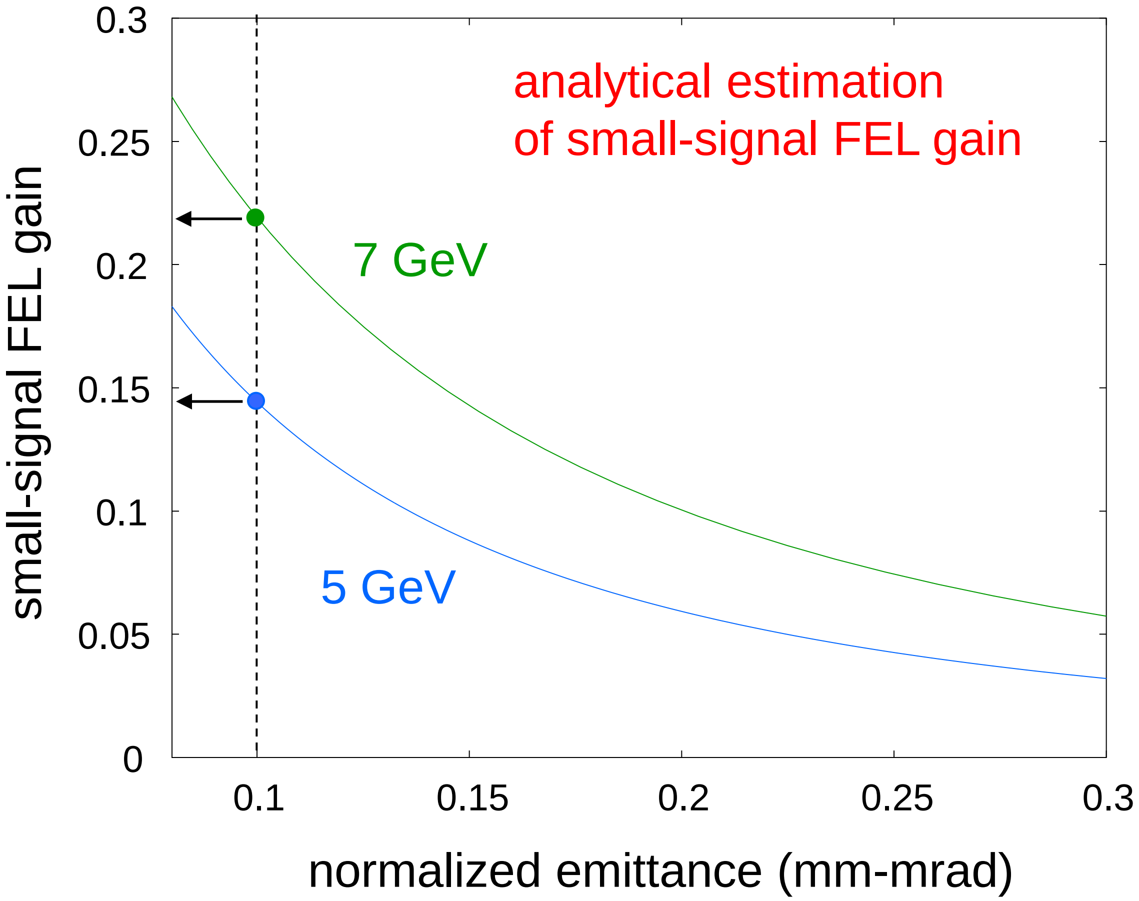
assuming same peak current and same mode area,

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

1-D gain for 5 GeV beam is “0.65 x 1-D gain for 7 GeV”

further gain reduction due to the emittance effect.

XFELO with 5 and 7-GeV ERLs

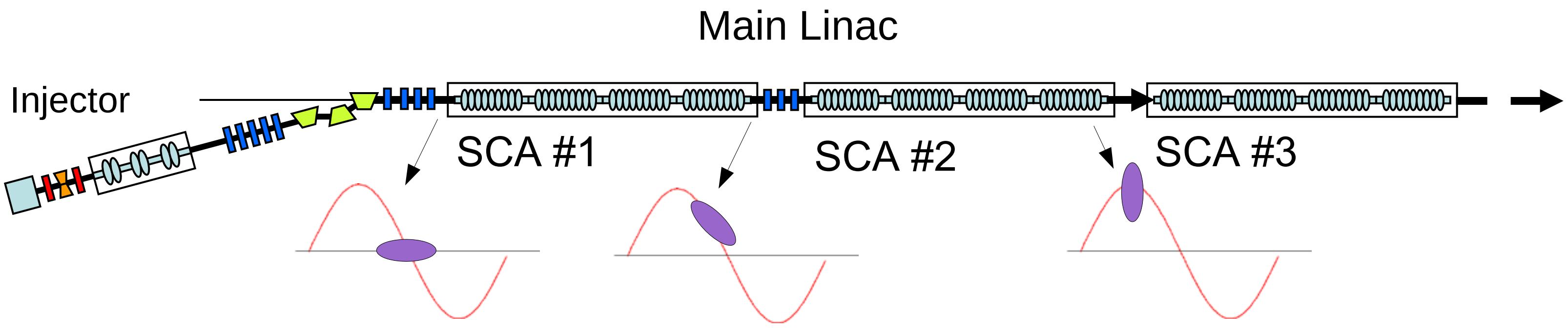


1Å X-FELO

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 %

The above calculations are based on a Halbach-type undulator.
DELTA undulator gives 1.4 times larger FEL gain.

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).

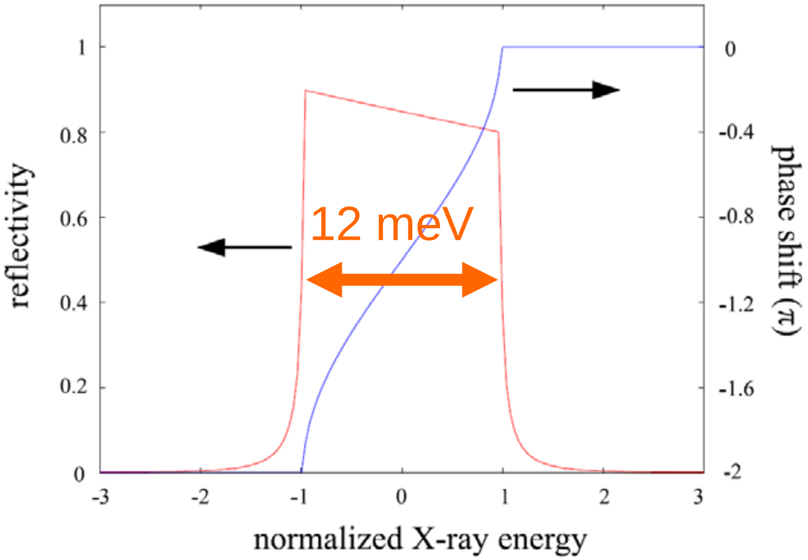
Velocity bunching for an X-FELO R. Hajima, N. Nishimori, FEL-2009

(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

Gain reduction by bandwidth mismatch

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

$$\underset{\text{growth rate of the } m\text{-th mode}}{\Lambda_m} = (\underset{\text{gain}}{g} - \underset{\text{loss}}{\alpha})/2 - \underbrace{(u/2\tau_M)^2}_{\text{cavity length detuning}} - \underbrace{0.5\sqrt{g}(2m+1)(\tau_M/\tau_{\text{el}})}_{\text{bandwidth mismatch}}$$



reflectivity and phase shift
for a cavity round trip

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

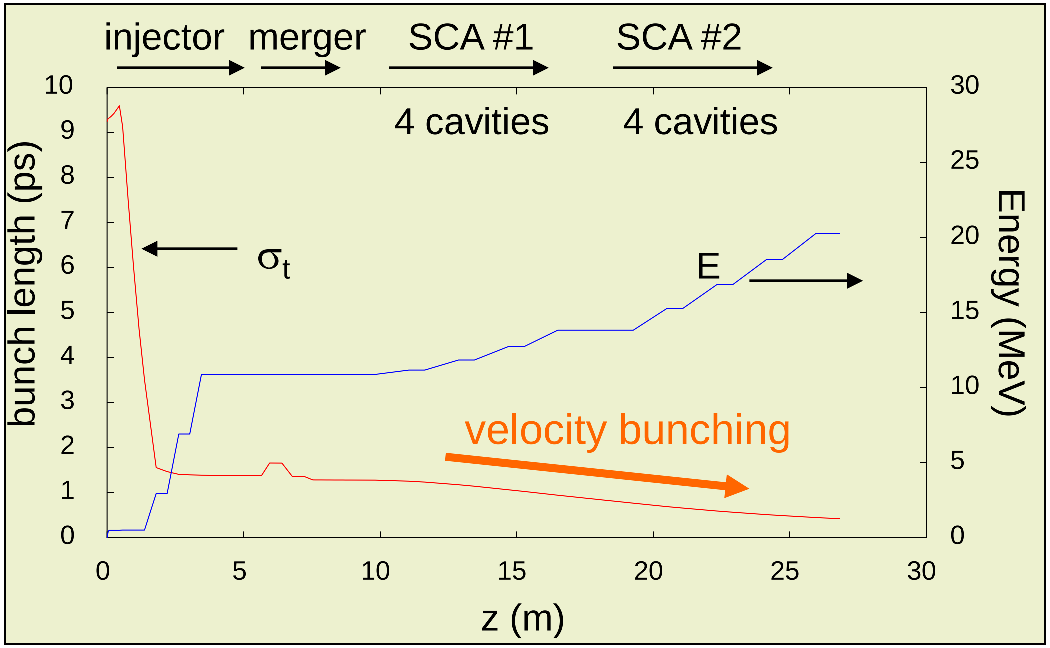
bandwidth of the Bragg mirrors = 12 meV

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

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

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

Example of the velocity bunching

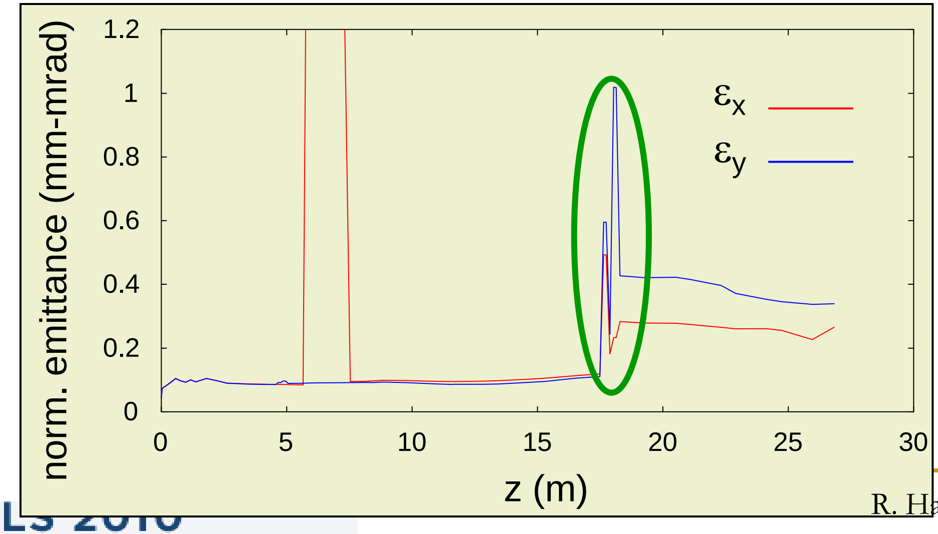


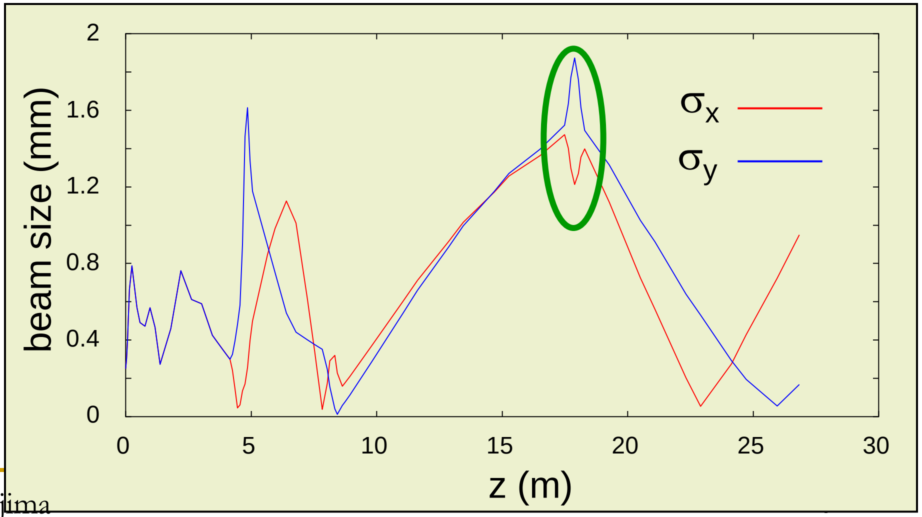
PARMELA simulation

bunch charge q = 7.7 pC

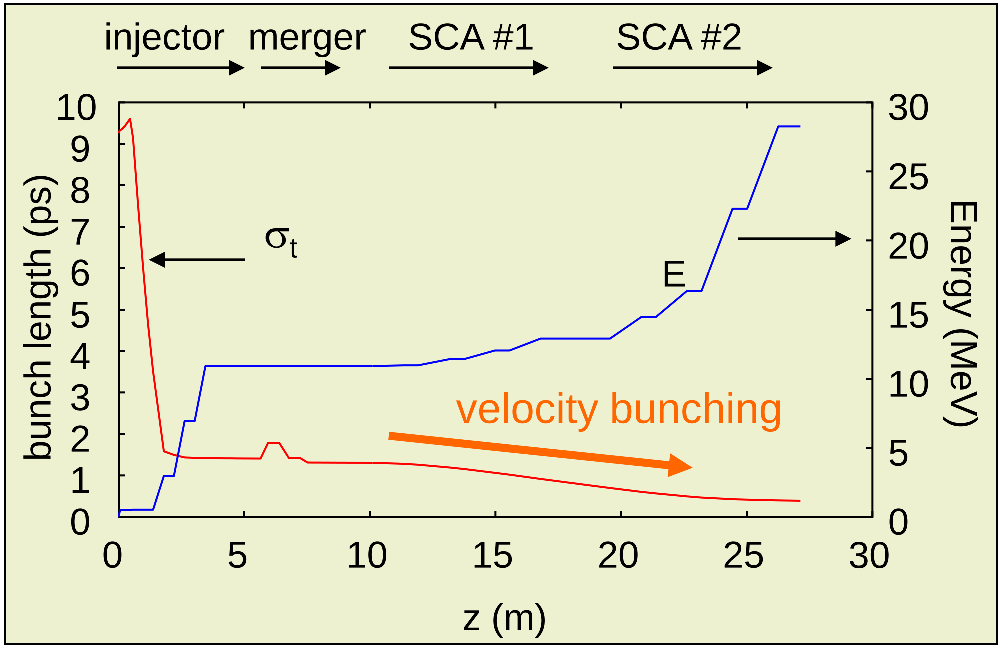
velocity bunching
bunching in 8 cavities
injection 10.9 MeV, 1.3 ps, -85 deg.
gradient E_{acc} = 8.5 MV/m

emittance growth by chromatic aberration





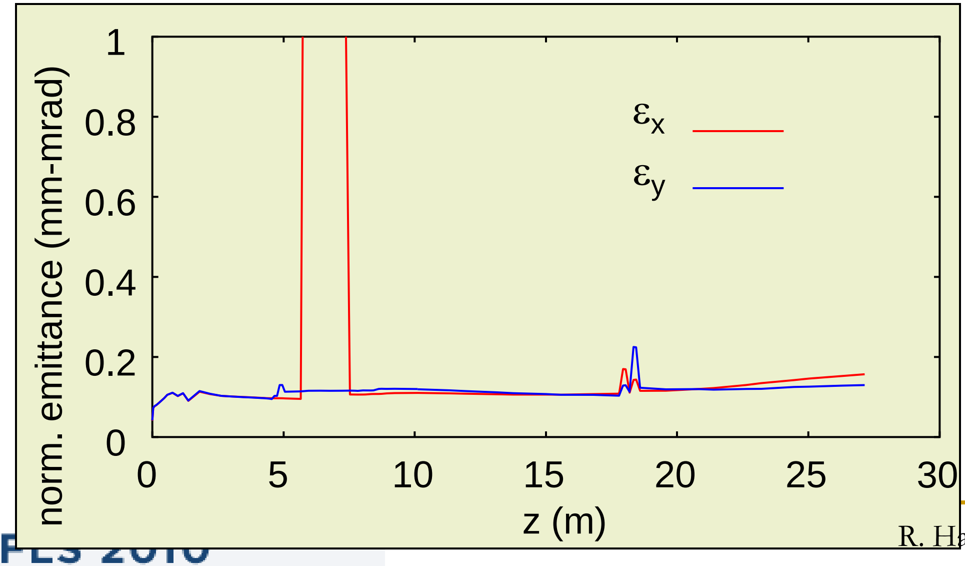
Optimum design of the velocity bunching

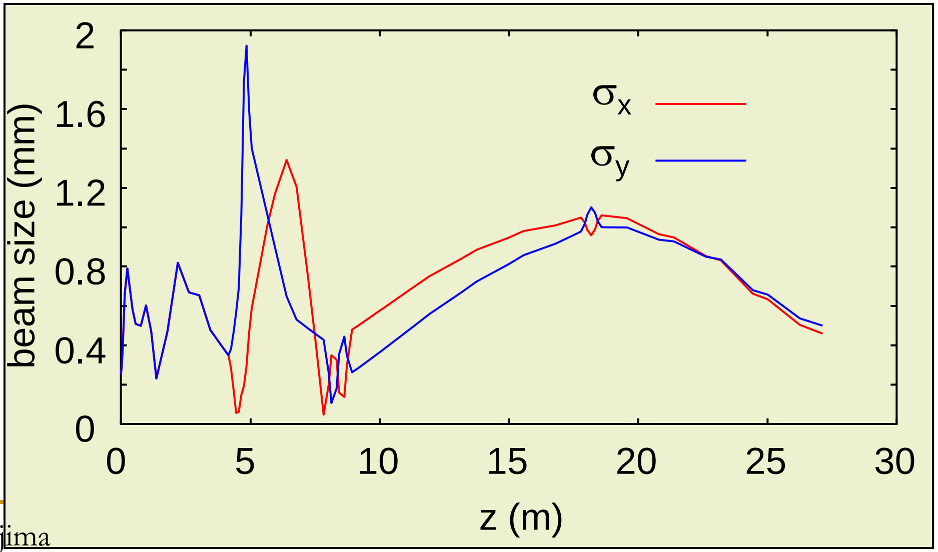


bunch charge $q = 7.7$ pC

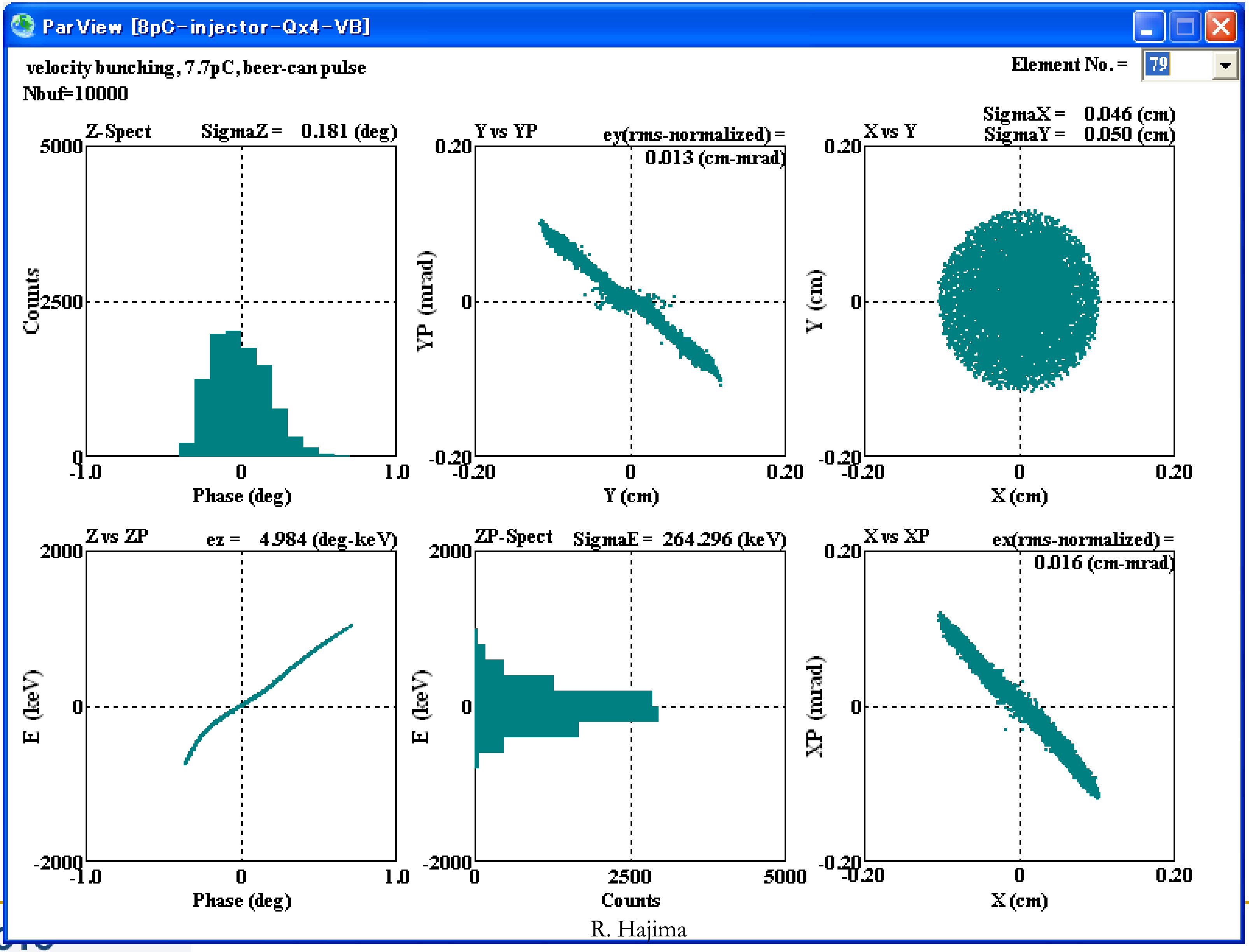
velocity bunching
bunching in 6 cav. + on-crest 2 cav.
injection 10.9 MeV, 1.3 ps, -90 deg.
gradient $E_{acc} = 8.5$ MV/m

at the SCA#2 exit
$E = 27.7$ MeV, $\sigma_t = 380$ fs, $\sigma_E = 250$ keV
$\varepsilon_x = 0.16$ mm-mrad, $\varepsilon_y = 0.13$ mm-mrad





Phase plot at the SCA #2 exit



velocity bunching, 7.7pC, beer-can pulse
Nbuf=10000

Element No. = 79

Z-Spect SigmaZ = 0.181 (deg)

Y vs YP ey(rms-normalized) = 0.013 (cm-mrad)

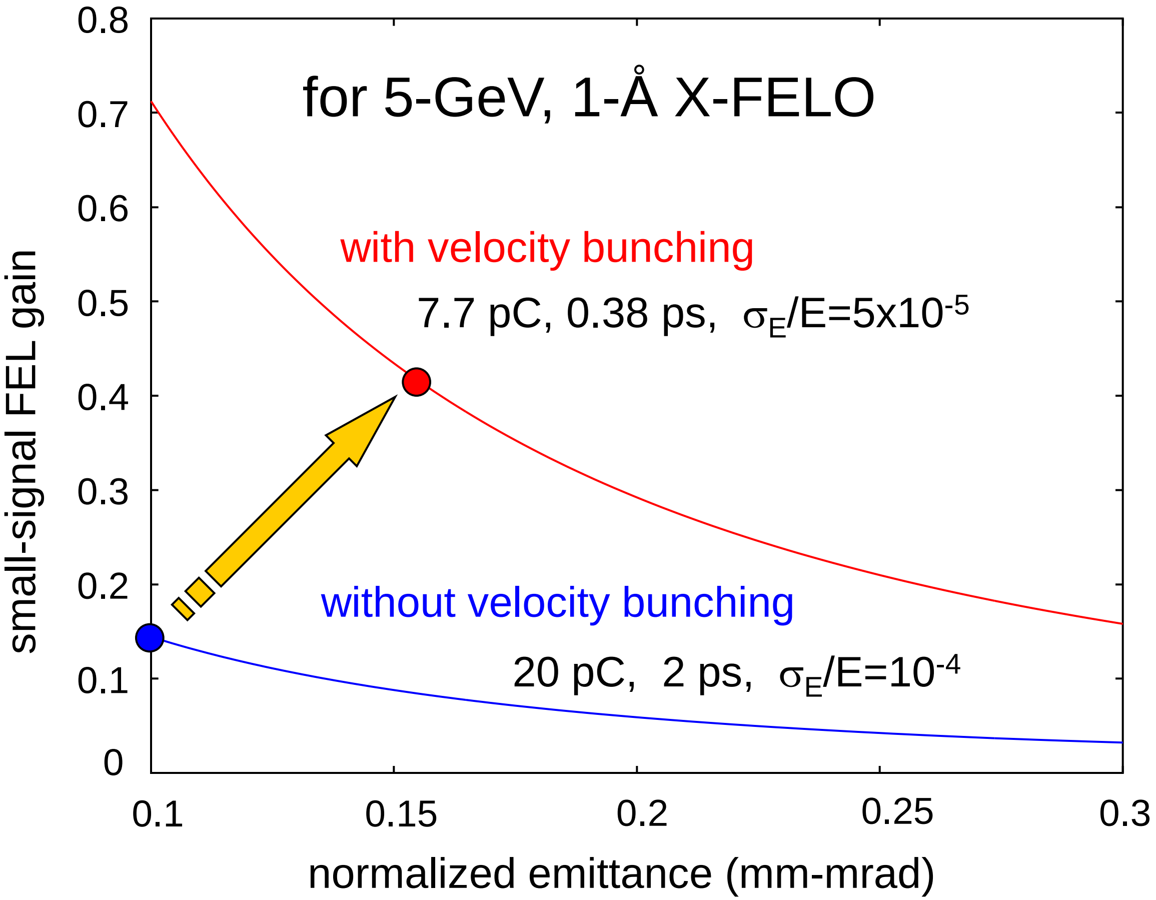
X vs Y SigmaX = 0.046 (cm) SigmaY = 0.050 (cm)

Z vs ZP ez = 4.984 (deg-keV)

ZP-Spect SigmaE = 264.296 (keV)

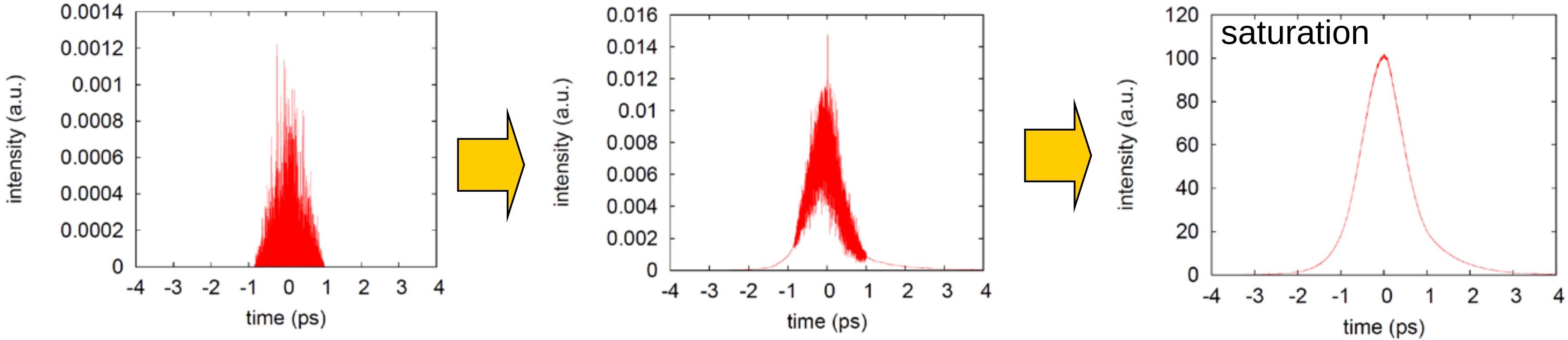
X vs XP ex(rms-normalized) = 0.016 (cm-mrad)

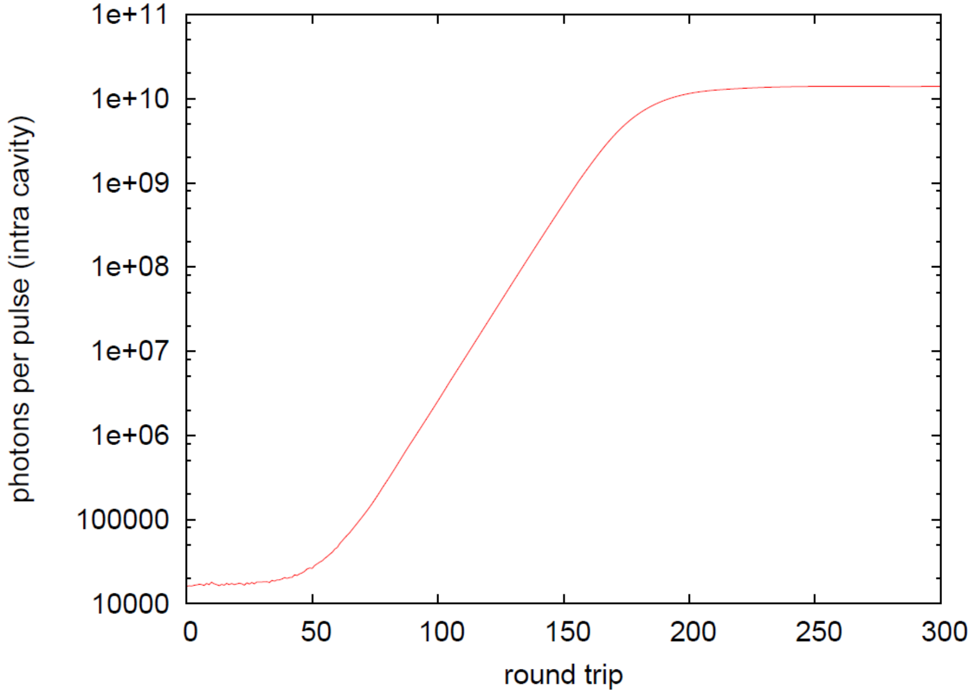
Enhancement of the FEL gain by velocity bunching



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

Simulation of XFELO (5 GeV with velocity bunching)





After the saturation:

pulse duration

τ=1.2 ps (FWHM)

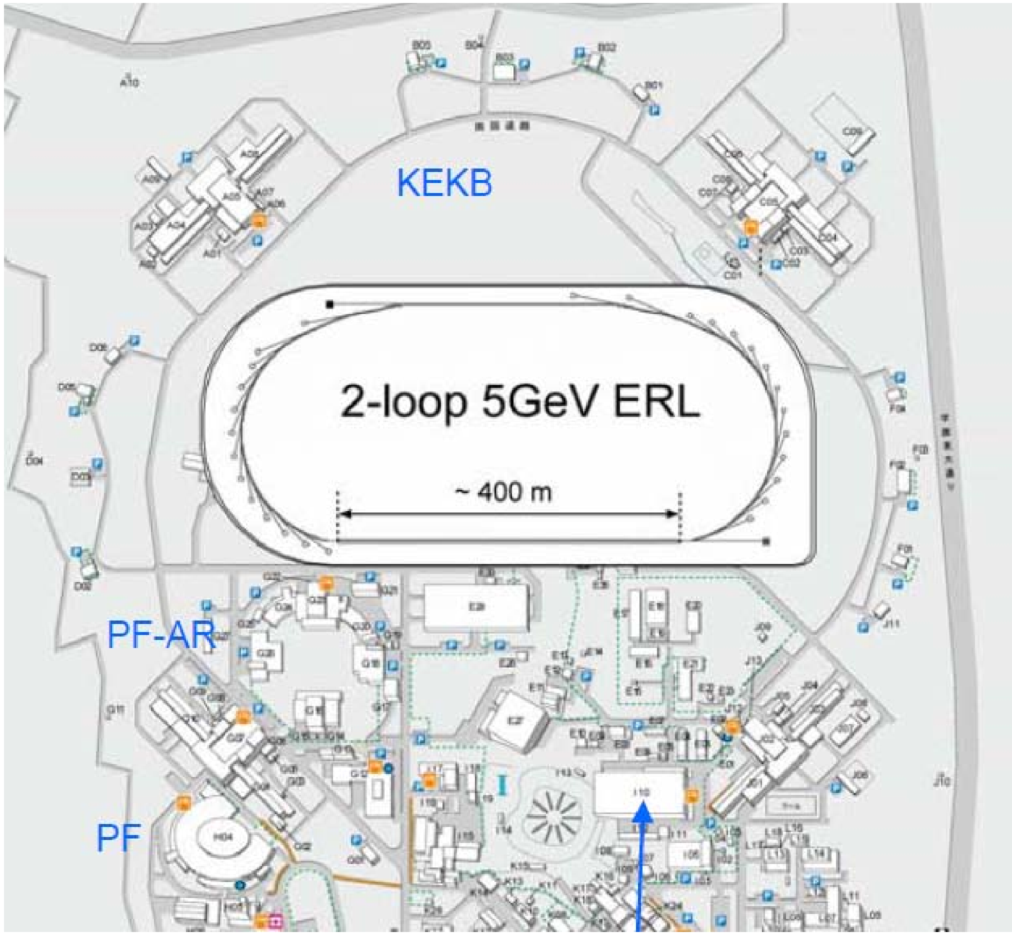
photons/pulse (intra cavity)

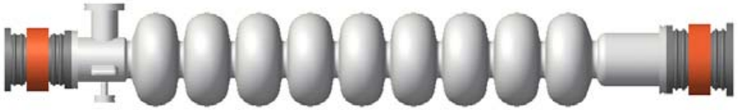
$N_p = 2\text{x}10^{10}$

photons/pulse (extracted)

$N_p = 7\text{x}10^{8}$

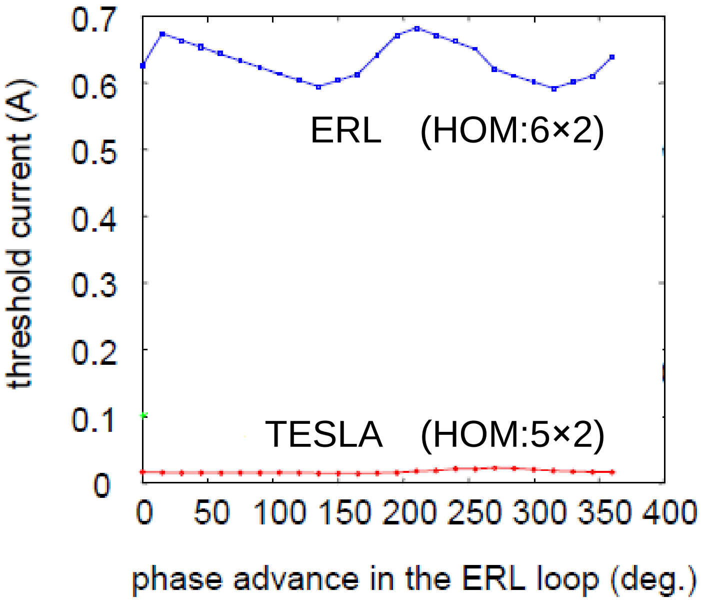
2-Loop Design of 5-GeV ERL





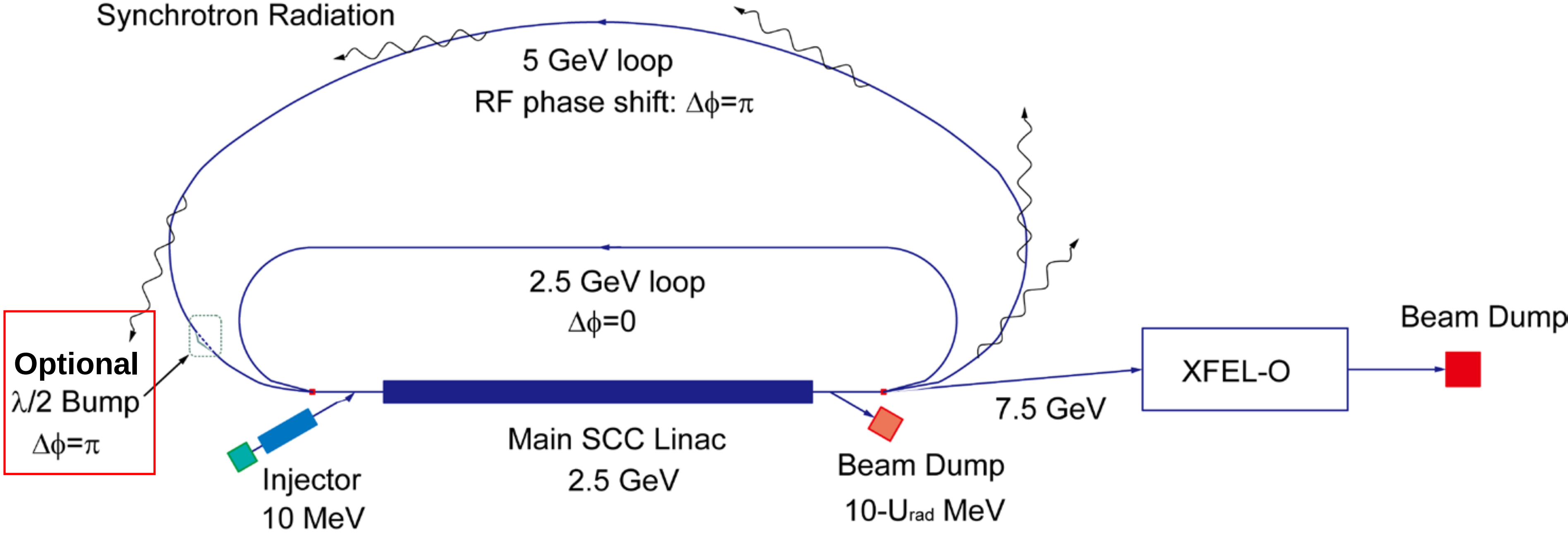
HOM-damped cavity

high threshold current of HOM BBU allows 2-loop configuration.



Possible Scheme for Combining ERL and XFELO

- 5 GeV ERL for SR use : accelerate 2 times
- 7.5 GeV recirculating linac for XFELO : accelerate 3 times



We can switch two operation modes by introducing an orbit bump having $\lambda_{rf}/2$= 11.5 cm.

S. Sakanaka, talk at PF-ISAC (2010)

Growth of emittance and e-spread for 3-pass 7.5-GeV

1st-loop: E=2.5 GeV, ρ=8.66m, 2x14-cell FODO $I_3 = 8.4\times10^{-2}(m^{-2})$ $I_5 = 2.8\times10^{-3}(m^{-1})$

2nd-loop: E=5 GeV, ρ=25m, TBAx30-cell $I_3 = 1.0\times10^{-2}(m^{-2})$ $I_5 = 4.6\times10^{-5}(m^{-1})$

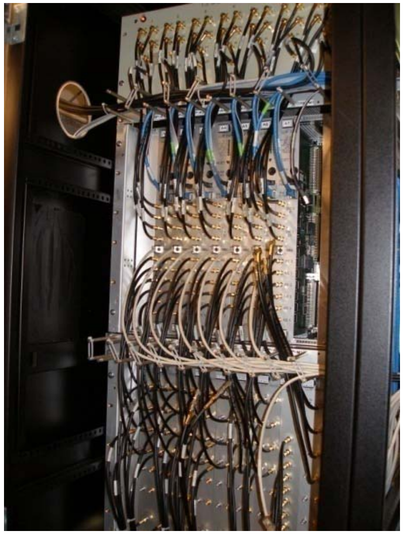
	$\Delta\varepsilon_n$	$\Delta\sigma_E$	
1st loop (2.5 GeV)		*8pC/400fs*	*20pC/2ps*
incoherent SR	0.029 mm-mrad	34 keV	34 keV
coherent SR	assumed to be compensated	37 keV	11 keV
2nd loop (5 GeV)			
incoherent SR	0.027 mm-mrad	130 keV	130 keV
coherent SR	assumed to be compensated	53 keV	16 keV

$$\varepsilon_n = \sqrt{\varepsilon_i^{\,2} + \Delta\varepsilon_c^{\,2} + \ldots} \qquad \varepsilon_n = 0.1 \rightarrow 0.11\mathrm{mm-mrad}$$

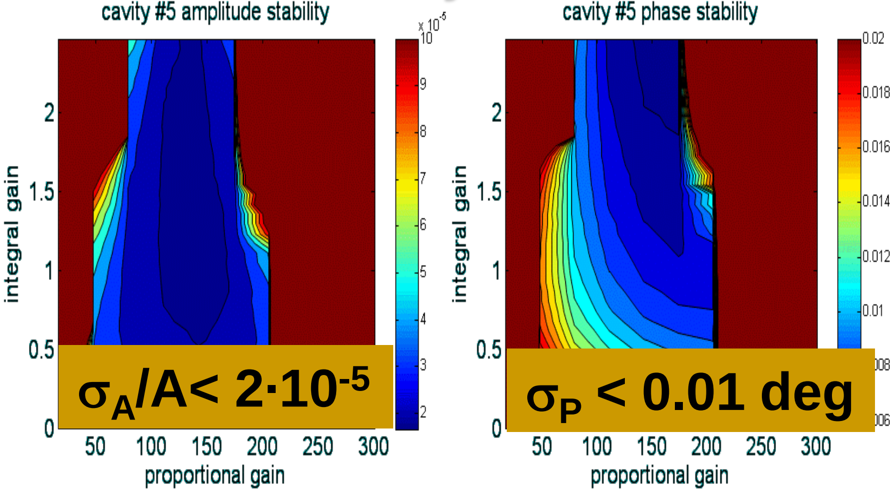
$$\Delta\sigma_E = \sqrt{\Delta\sigma_{E,i}^{\,2} + \Delta\sigma_{E,c}^{\,2} + \ldots} \qquad \Delta\sigma_E/E = 2 \times 10^{-5}$$

acceptable for FEL

Stability of SRF



Cornell LLRF System



$\sigma_A/A < 2\cdot10^{-5}$

$\sigma_P < 0.01$ deg

Demonstrated:

- **Exceptional field stability at $Q_L = 10^6$ to 10^8**
- **Lorentz-force compensation and fast field ramp up**
- **Piezo microphonics compensation with ~20 Hz bandwidth**

M. Liepe, ERL-09

energy stability << FEL gain band width $\frac{1}{2N_u} = 1.7\times10^{-4}$ for $N_u = 3000$

This requirement is fulfilled by current LLRF technology.

Conclusions

- Hard X-ray ERL can accommodate XFELO.
  - we can extend the frontier of X-ray beam parameters
- 0.1nm-XFELO is feasibly realized at
  - 5-GeV ERL with velocity bunching
  - 7.5-GeV beam from a 2-loop 5-GeV ERL
  - an ERL injector is shared, no major modification is needed
- XFELO can be installed either at a loop or a branch.
  - however, beam loss in a long narrow duct might be a problem for a XFELO in a loop

- In the Japanese collaboration, XFELO is considered as a part of 5-GeV hard X-ray ERL.