清華大學
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Advanced concepts for future SSMB storage rings

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Outline

- Introduction to SSMB (steady-state microbunching)

- The GLSF (generalized longitudinal strong focusing) scheme

Towards high-power light sources

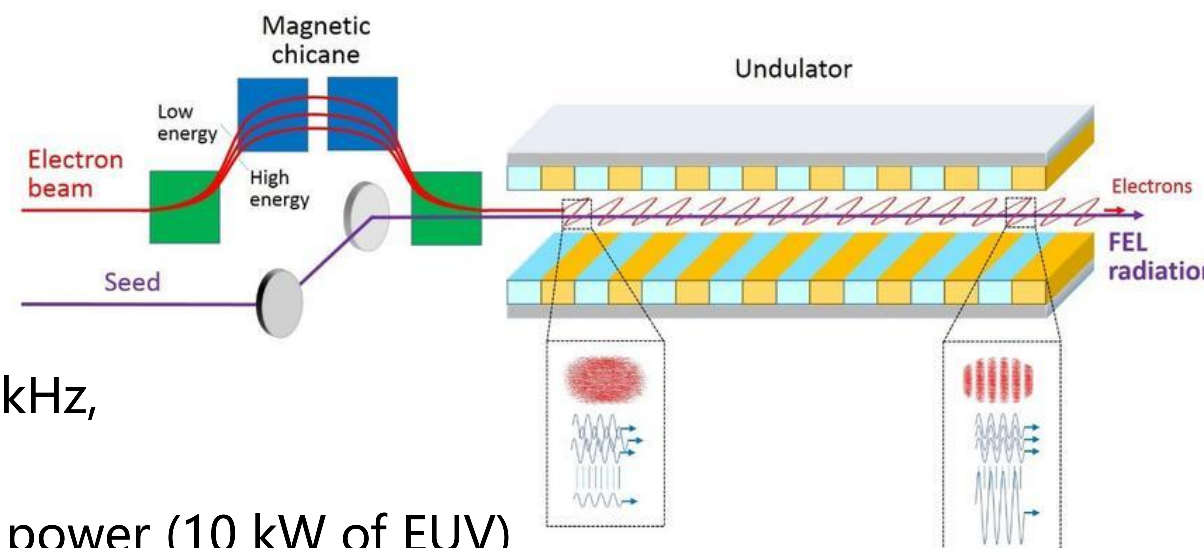
Synchrotron radiation sources:
High repetition rates; Good transverse coherence;
Poor longitudinal coherence (short-wavelength).

Incoherent radiation $P \propto N_e$

Coherent radiation $P \propto N_e^2$

For EUV, average power is around Watt in 2% b.w.

Free-electron lasers:
Good coherence;
(trans. AND long.)



Repetition rates:
NC: hundreds of Hz or kHz,
SC: up to the MHz
high average radiation power (10 kW of EUV)
Concern is the cost.

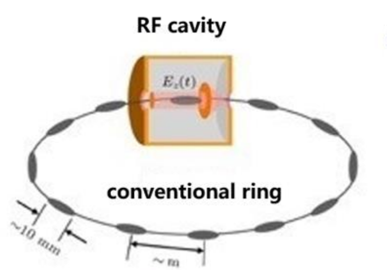
Steady-state microbunching

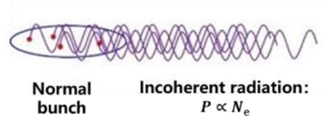
A new mechanism of accelerator-driven light source

Generate microbunching and maintain it in storage rings, without destroying the bunch when radiation.

strong coherence
high repetition rate

Synchrotron radiation(SR)



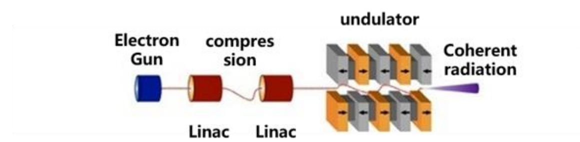


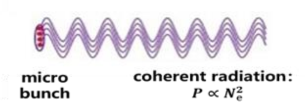
$P \propto N_e$

$f \sim 10^6 Hz$

High repetition rate
Low peak power

Free electron laser(FEL)



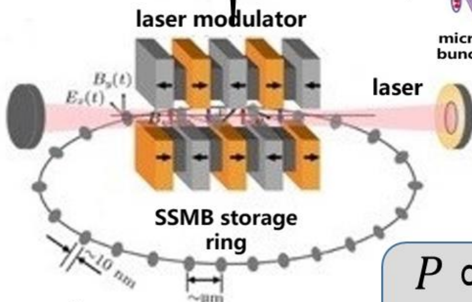


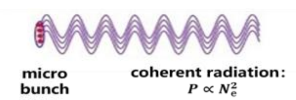
$P \propto N_e^2$

$f \sim 10^2 Hz$

Low repetition rate
High peak power

Steady state micro-bunching (SSMB)





Laser modulator instead of RF cavity

$P \propto N_e^2$

$f \sim 10^6 Hz$

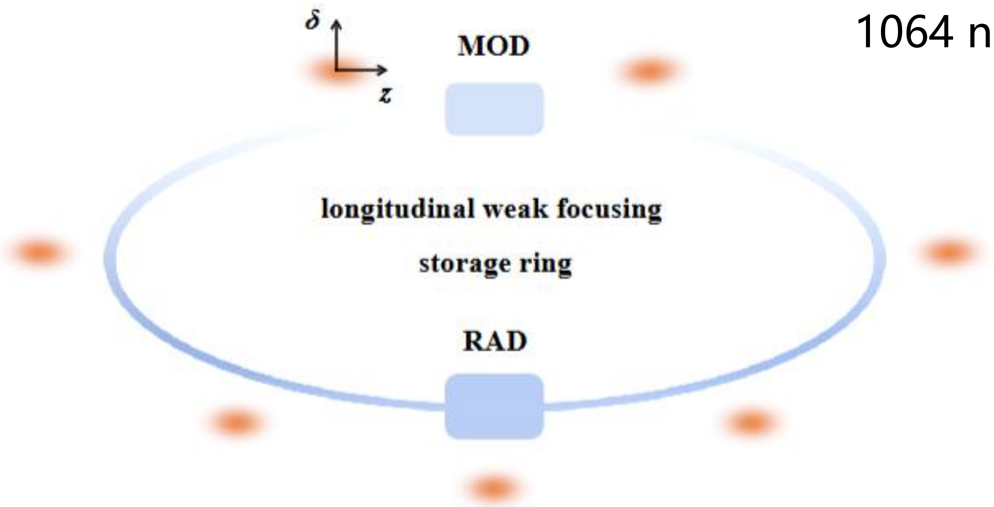
High average power (kW of EUV)

High repetition rate
High peak power

D. F. Ratner and A. W. Chao, Phys. Rev. Lett. 105, 154801 (2010).

Approaches to realize **eigenstate** nanometer-long bunches in storage rings?

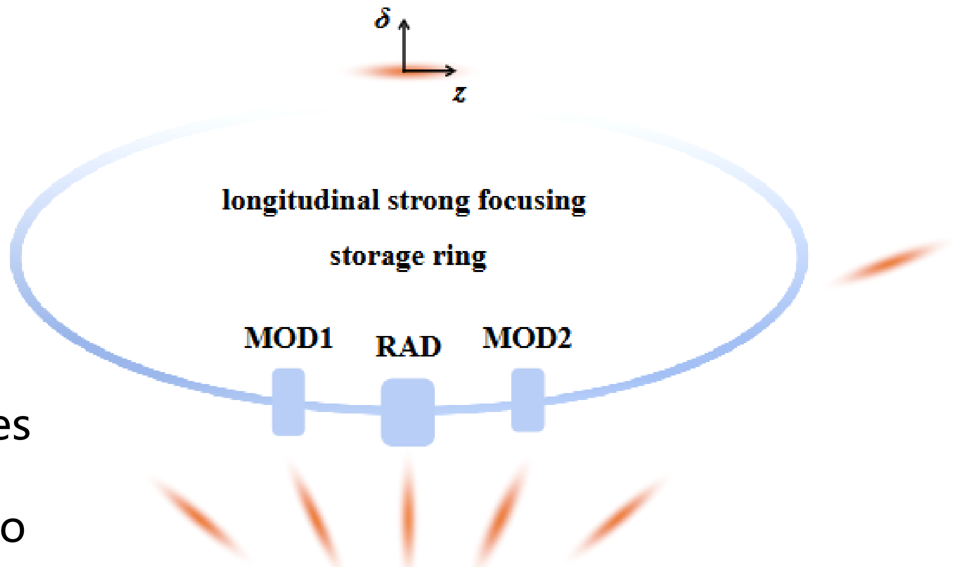
Longitudinal weak focusing (LWF): laser modulator + low-α lattice



1064 nm, MW-level ~1e-6

tens-of-nanometer-long bunch can be achieved; hard to get coherent radiation at 13.5 nm (EUV).

Longitudinal strong focusing (LSF):
Laser modulators as 'long. quads'



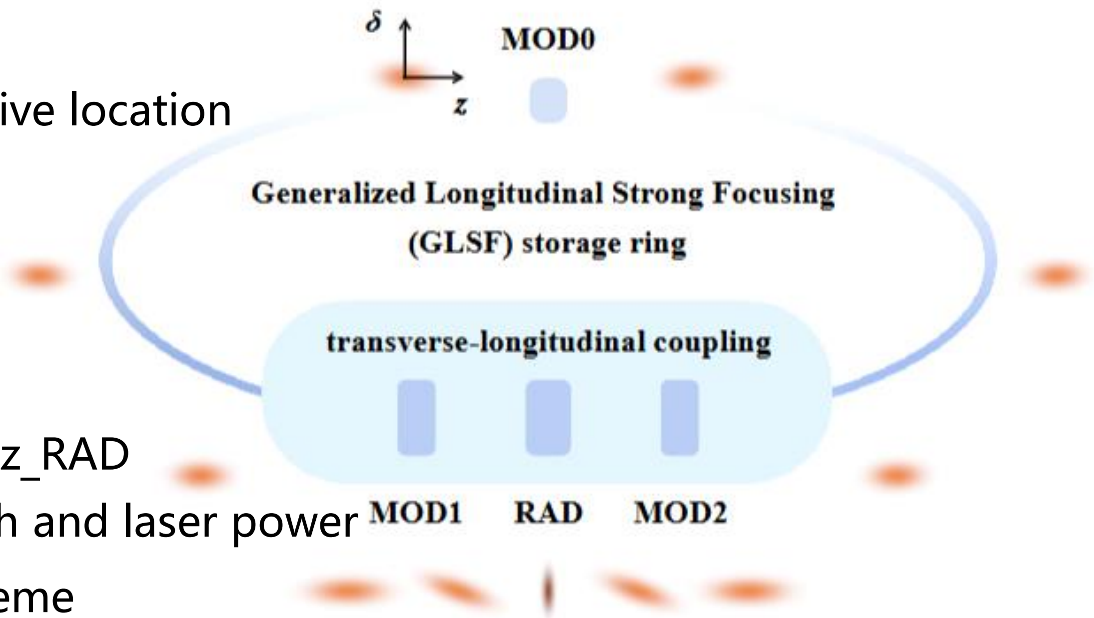
Notable variation of bunch length
At radiation point nanometer-long bunches
Coherent 13.5-nm EUV radiation
Hundreds of MW laser power is required to modulate the beam → pulsed mode

Generalized longitudinal strong focusing

Generalized longitudinal strong focusing (GLSF):
Strong beam manipulation, yet within 4-D coupled phase space

Vertical-longitudinal coupling

Laser modulator placed at dispersive location



$(\epsilon_x, \epsilon_y, \epsilon_z)$ $\sigma_{z\_\mathrm{RAD}} \propto \sqrt{\epsilon_y}$

P_{laser} ↓

Project exclusively low emit_y to σz_RAD

Less demand on modulation depth and laser power

A partial emittance-exchange scheme

De-modulation and de-coupling are needed to match beam status with the rest of the ring outside the GLSF unit → Ring-based eigen-state

works also for RF-pre-bunched and coasting beam

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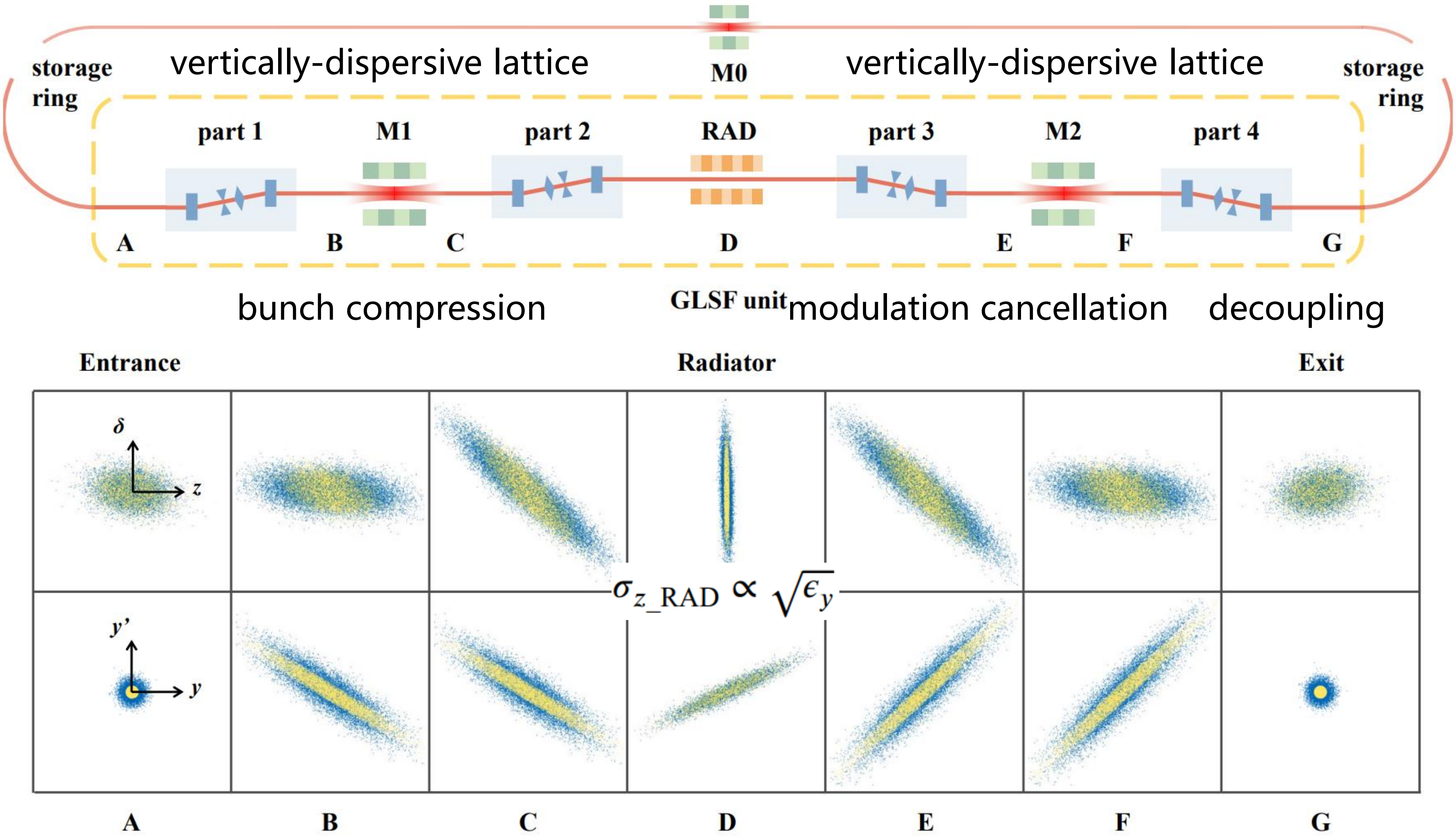
GLSF unit



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Bunching factor

Bunching factor for pre-bunched beam at the radiation point in GLSF approach

$$b = e^{-\frac{1}{2}k_r^2\sigma_{z\_RAD}^2}\left|\sum_{p=-\infty}^{\infty} J_p(n)\, e^{-\frac{1}{2}(n-p)^2 k_m^2 \sigma_{z\_MOD}^2}\right|$$

$J_p(n)$ p-th order Bessel function of first kind

n: harmonic number

kr/km: radiation/modulation wave number

σz_RAD/σz_MOD: bunch length at RAD/MOD

modulation depth h

$$|h| \geqslant \frac{\epsilon_y}{\sigma_{z\_y\_MOD}\sigma_{z\_RAD}}$$

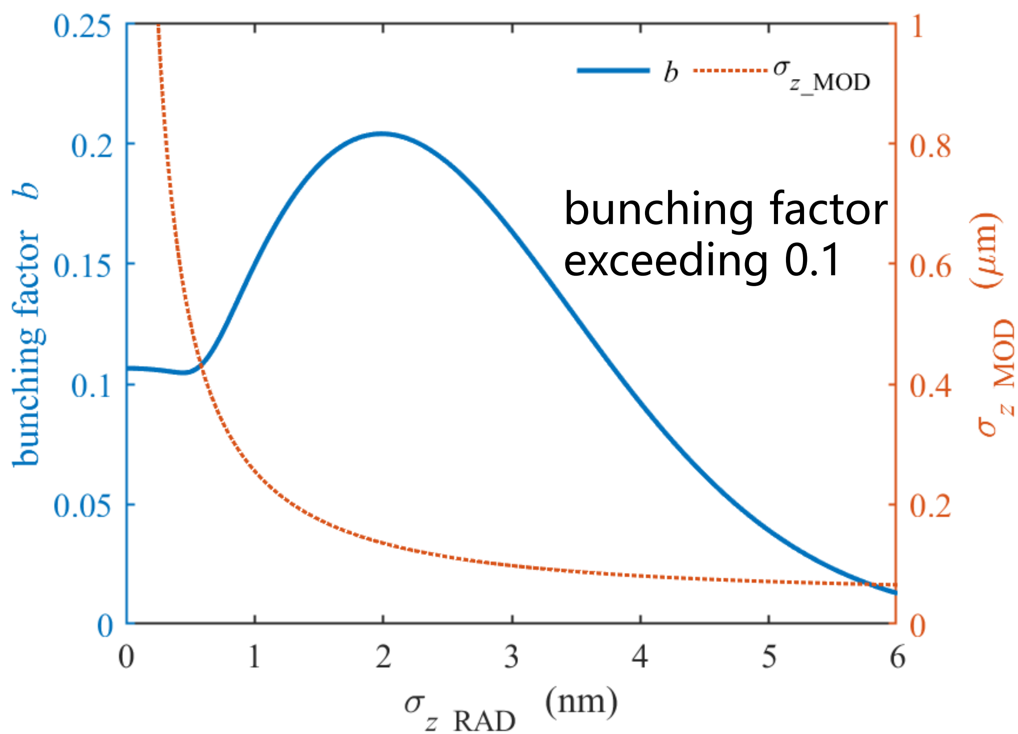
$$P_{RAD} \propto b^2$$

$$P_{laser} \propto h^2$$

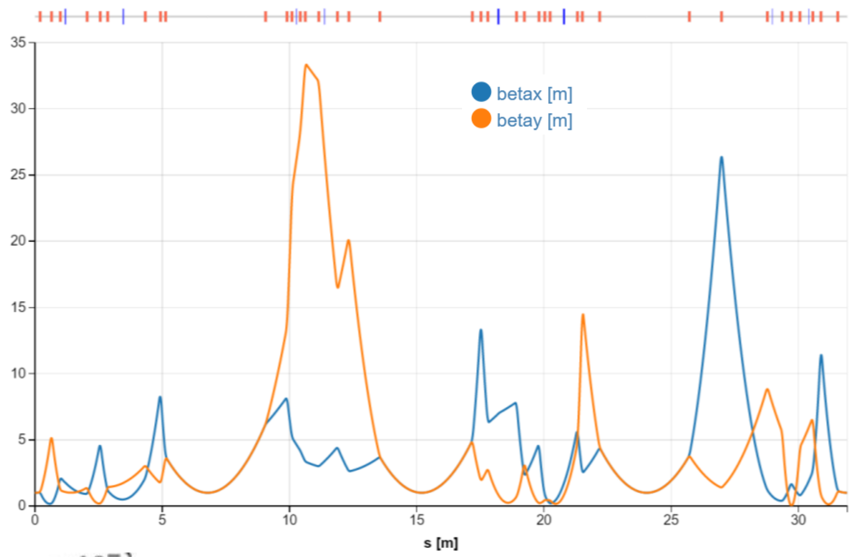
Low emit_y → low h and P_laser

This is why GLSF is preferred

Assuming
P_laser = 1 MW, |h| = 4000 m^{-1},
E = 400 MeV, emit_y = 1 pmrad,
λ_r = 13.5 nm, λ_m = 1 um,
σz_y_MOD = emit_y / (|h|*σz_RAD)



Linear demonstration of GLSF SSMB



E = 400 MeV

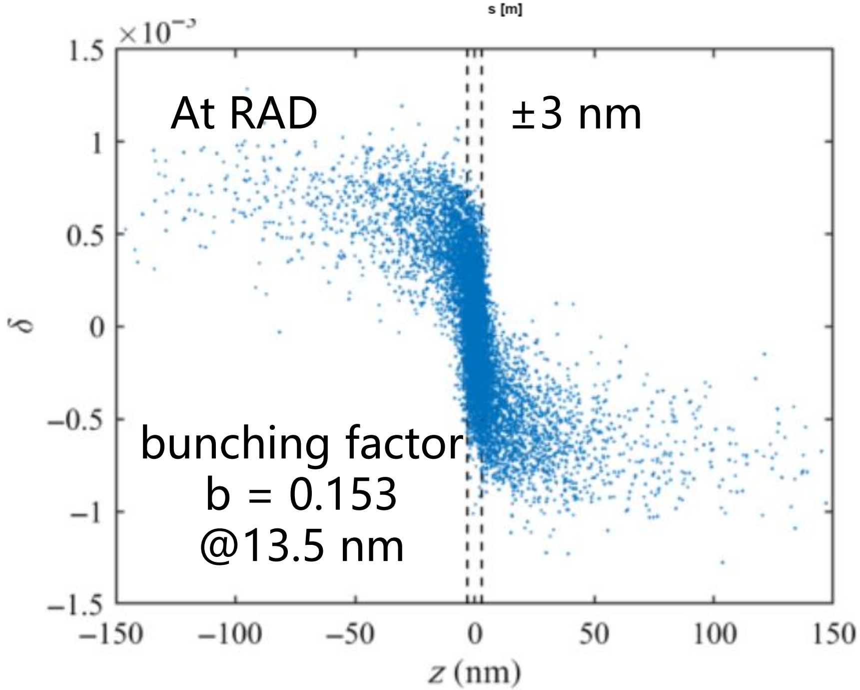
I_avg = 1 A

emit_y = 1 pmrad

λ_m = 1064 nm

λ_r = 13.5 nm

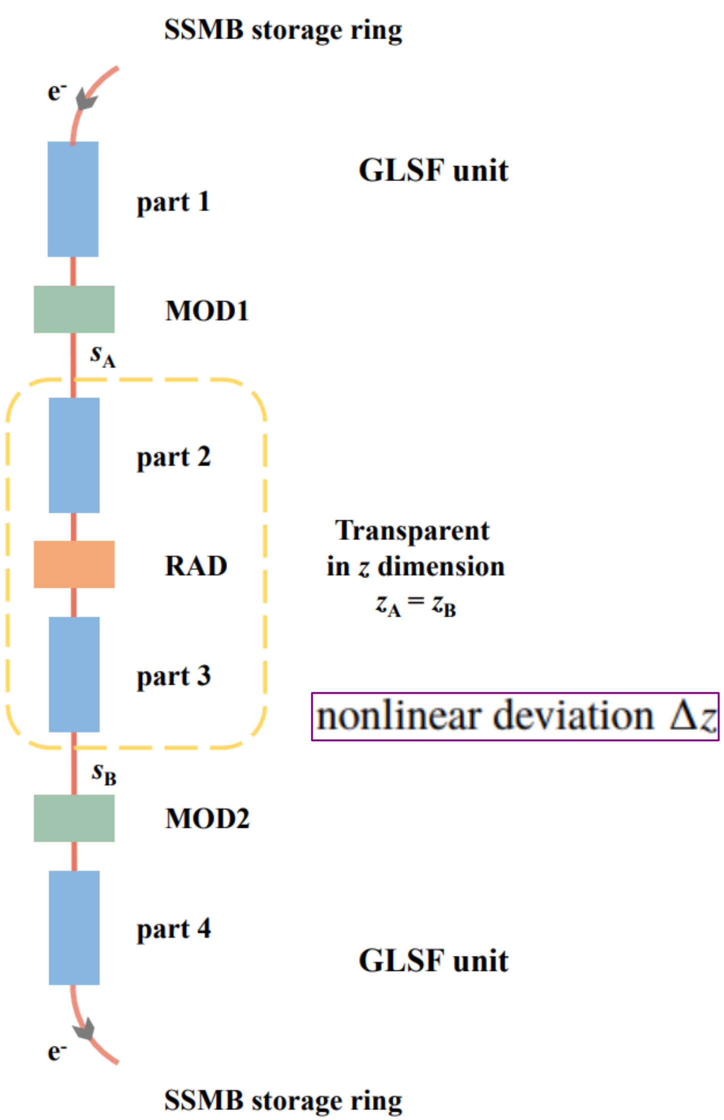
P_laser = 1 MW



EUV radiation within ±2% b.w. @ 13.5 nm: P=1.2 kW

With the linear design of the GLSF unit completed, an output of kilowatt-level EUV radiation is attained for the first time within the current technical capabilities of laser cavities.

GLSF nonlinear issues



- Express Δz in terms of the particle coordinates at s_A using the Taylor-map representation.
- Derive the expressions for $\langle\Delta z\rangle$ and $\sigma_{\Delta z}$.
- Evaluate the 2nd and 4th-order beam moments at s_A and substitute them into $\langle\Delta z\rangle$ and $\sigma_{\Delta z}$ expressions.
- Sort expressions for $\langle\Delta z\rangle$ and $\sigma_{\Delta z}$ by beam parameters, namely ϵ_x, ϵ_y, σ_{δ_0}, as well as h.

$$\langle\Delta z\rangle = \epsilon_x\Omega_1 + \epsilon_y\Omega_2 + \sigma_{\delta_0}^2\Omega_3 + \frac{h^2}{2k^2}\Omega_4$$

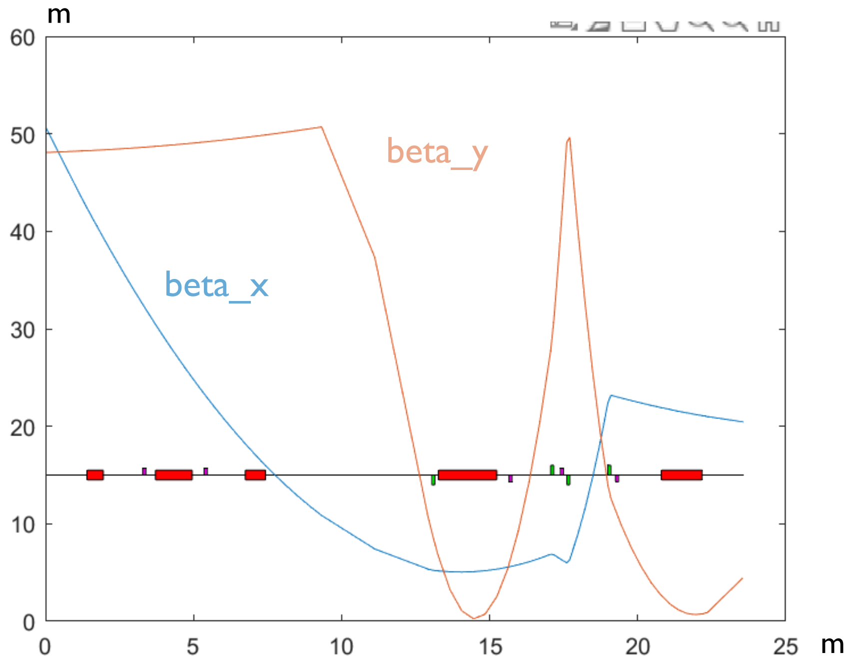
$$\sigma_{\Delta z}^2 = \epsilon_x^2\Sigma_1 + \epsilon_y^2\Sigma_2 + \epsilon_y\sigma_{\delta_0}^2\Sigma_3 + \epsilon_y\frac{h^2}{k^2}\Sigma_4 + \sigma_{\delta_0}^4\Sigma_5 + \sigma_{\delta_0}^2\frac{h^2}{k^2}\Sigma_6 + \frac{h^4}{k^4}\Sigma_7$$

$$\Omega_1 = T_{511}\beta_x - 2T_{521}\alpha_x + T_{522}\gamma_x$$
$$\Omega_2 = T_{533}\beta_y - 2T_{543}\alpha_y + T_{544}\gamma_y$$
$$\Omega_3 = T_{533}D^2 + 2T_{543}DD' + T_{544}D'^2 + 2T_{563}D + 2T_{564}D' + T_{566}$$
$$\Omega_4 = T_{566}$$

Li, Zizheng, et al. IPAC2024-MOPS20

Nonlinear Δz optimization

Realization of lattice between modulators. Tried different layouts.
MOGA is used to find solutions. Goal is $\langle \Delta z \rangle$ and $\sigma_{\Delta z}$.



E = 600 MeV
h = 2560 m^{-1}
Hy_rad = 0.87 μm
Hy_mod = 0.19 m

beta_max = 50.7 m
beta_min = 0.25 m
eigen-emit_y = 1.19 pmrad
rho = 65.6 m

emit_x = 5.13 nmrad
emit_y = 4.60 pmrad
sigma_delta = 9.44e-4
λ_m = 532 nm

Sextuple off	**Sextuple on**
$\langle \Delta z \rangle = 13\ \mathrm{nm}$	$\boldsymbol{\langle \Delta z \rangle = 0.06\ \mathrm{nm}}$
$\sigma_{\Delta z} = 17\ \mathrm{nm}$	$\boldsymbol{\sigma_{\Delta z} = 0.09\ \mathrm{nm}}$

Summary

- SSMB is a novel light source with the capability of generating high-average-power short-wavelength coherent radiation.

- The GLSF approach can establish nanometer-long ring-stored bunches through beam manipulation in 4-D vertical-longitudinal coupled phase space. In linear demonstrations, an output of kilowatt-level EUV radiation can be realized within the current technical capabilities of laser cavities.

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Generalized longitudinal strong focusing in a steady-state microbunching storage ring

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Thank you for your time.