Three-Dimensional Manipulation of the Electron Beam Phase Space for Generating Intense Coherent Radiation in Storage Rings

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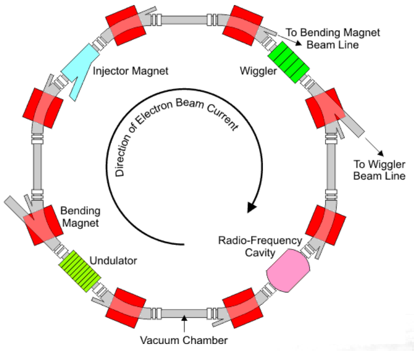
Outline

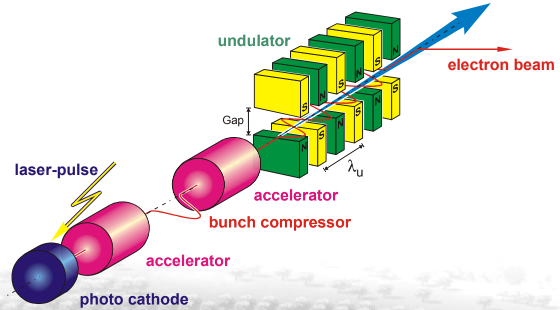
- Advanced accelerator based EUV/x-ray sources
- Ideas for manipulating the electron beam in storage rings
- A new scheme for generating intense ultra-fast coherent radiation pulse
- Reversible seeding for SSMB with the proposed scheme
- Summary

Advanced accelerator based EUV/x-ray sources

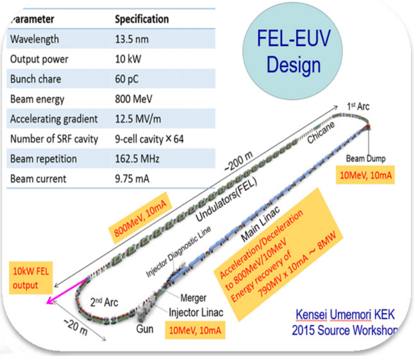
technological maturity



Storage ring



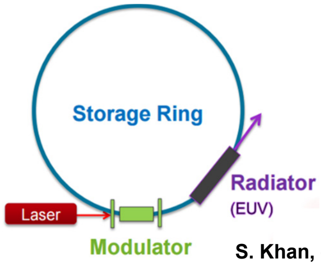
Free-electron laser (FEL)

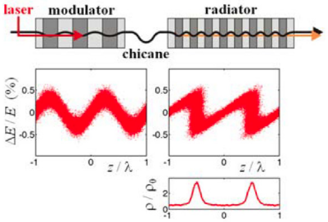


Superconducting energy-recovery linac (ERL)

	High repetition rate	High peak Power (not required for lithography)	High average power	Coherence	technological maturity	Multi-beam line
Storage ring	√	×	×	×	√	√
FEL	×	√	×	√	√	×
ERL	√	√	√	√	×	×

Ideas for improving the performance of storage ring based EUV light sources





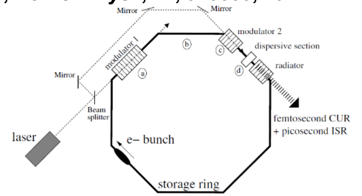
S. Khan, et al. *Sync. Rad. News* 26, 25–29 (2013).

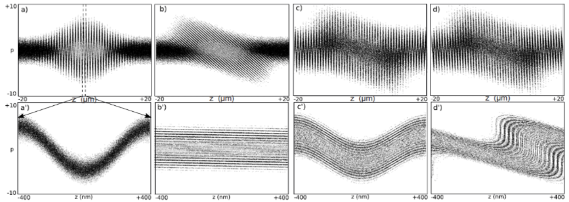
- Combine the advantages of high peak power of FEL and High repetition rate of storage ring
- The basic idea is to introduce coherent micro-bunching into the electron beam to enhance the output power by $10^{4\sim5}$
- The simplest way is based on CHG, however, the beam energy spread is too large
- Damping time significantly reduce the repetition rate

Two-Dimensional Manipulation

EEHG

C. Evain, *New J. Phys.* , 14, 023003, 2012

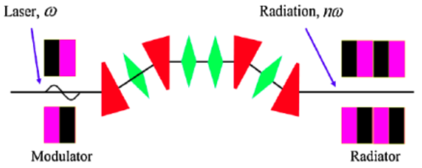


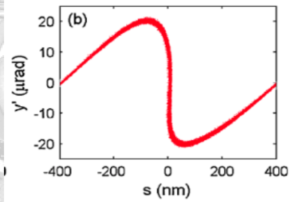


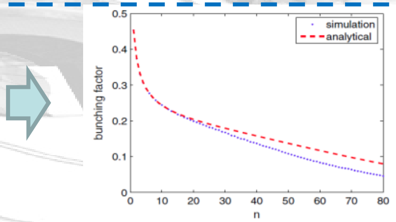
- Possible for generating EUV radiation.
- A relative complicated lattice design and high seed laser power

Angular modulation

D. Xiang, and W. Wan, *Phys. Rev. Lett.* 104, 084803 (2010)







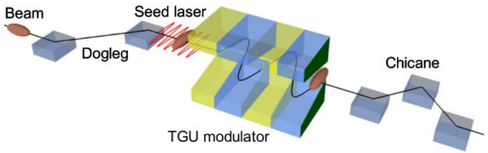
- Generating ultra-high harmonic radiation with small energy modulation
- Require very high seed (~TW) abd TEM01 mode may be not suitable for UV seed lasers

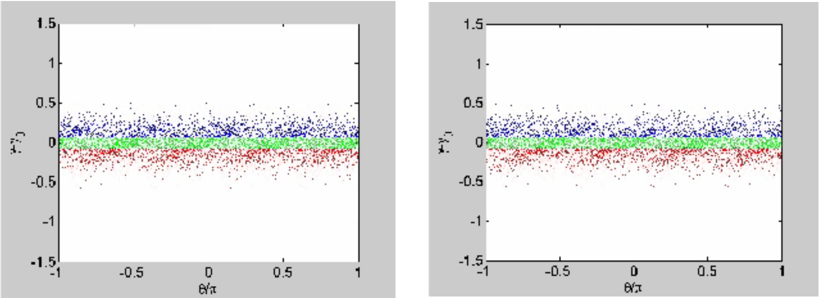
Ideas for improving the performance of storage ring based EUV light sources

Three-Dimensional Manipulation

PEHG

H. Deng, C. Feng, *Phys. Rev. Lett*. 111 (2013) 084801.
C. Feng, H. Deng, D. Wang, Z. Zhao, *New J. Phys*. 16 (2014) 043021

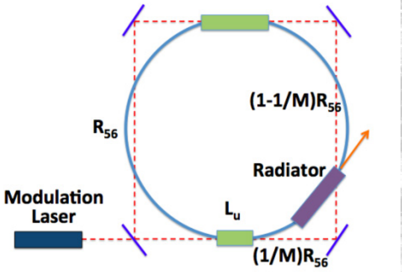


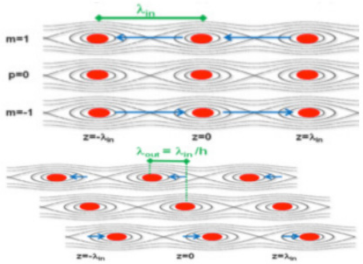


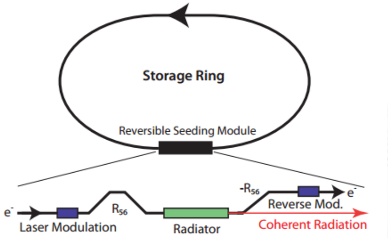
- Very high harmonic up-conversion efficiency with small energy modulation
- A special lattice design for the dogleg is needed to maintain the large bunching factor

Steady state micro-bunching (SSMB)

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



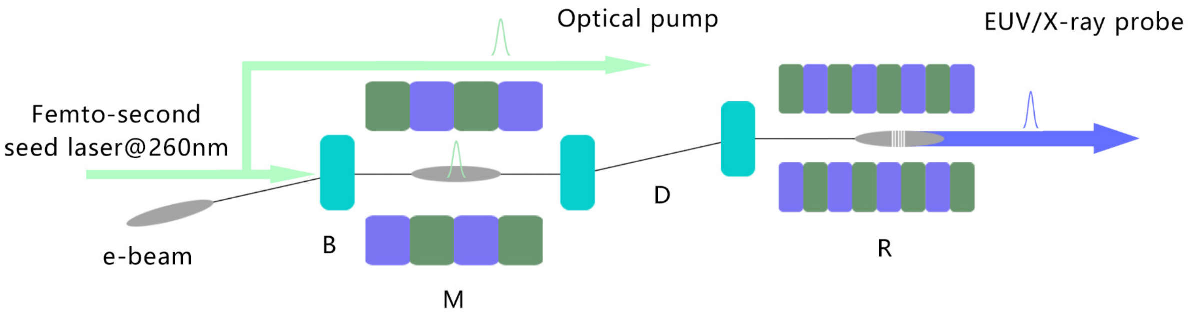




D. Ratner, A. Chao. In FEL 2011

- A possible technique for generating high average power coherent EUV radiation
- For reversible HGHG, the harmonic conversion number is low

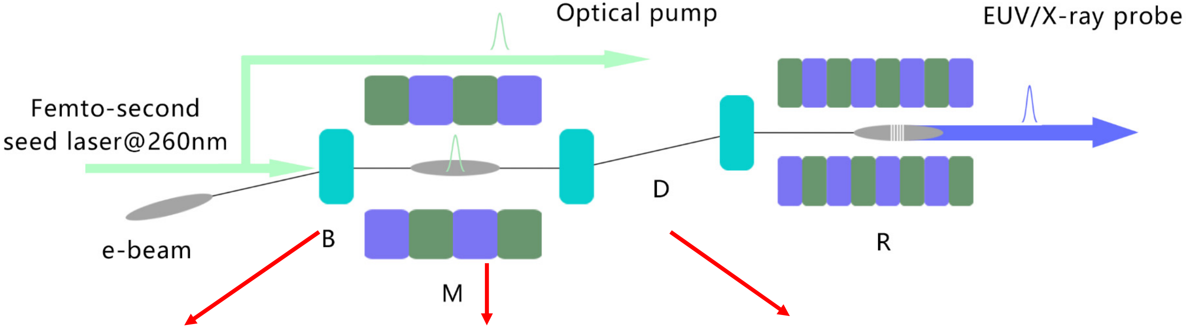
Layout of a new seeding scheme for generating ultra-short pulse in storage ring



- Consists of a seed laser, a bend (B), a modulator (M), a dispersion (D) and a radiator (R).
- An ultra-short laser@260nm with pulse duration of 30fs (FWHM) is adopted for the femtosecond slicing purpose
- Ultra-short soft x-ray radiation can be generated

C. Feng, Z. Zhao, Scientific reports, 7, 4724 (2017)

Optimization of the proposed seeding scheme



$$R_B = \begin{pmatrix} 1 & L_B & 0 & 0 \\ 0 & 1 & 0 & -b \\ b & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad R_M = \begin{pmatrix} 1 & L_M & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & h & 1 \end{pmatrix} \quad R_D = \begin{pmatrix} 1 & L_D & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$R = R_D \cdot R_M \cdot R_B = \begin{pmatrix} 1+hb\eta & L & h\eta & \eta-(L-L_b)b \\ 0 & 1 & 0 & -b \\ b(1+h\xi) & \eta & 1+h\xi & \xi-\eta b \\ hb & 0 & h & 1 \end{pmatrix}$$

$$1+h\xi_D = 0 \qquad \xi-\eta b = 0$$

$$b_n = J_n\left(nk_s\xi\frac{\Delta\gamma}{\gamma}\right)e^{-\frac{1}{2}(nk_s\eta\sigma_{y'})^2}$$

- Bunching factor is determined by the initial y’
- Lattice is relative simple
- Energy modulation can be much smaller than the initial energy spread

C. Feng, Z. Zhao, Scientific reports, 7, 4724 (2017)

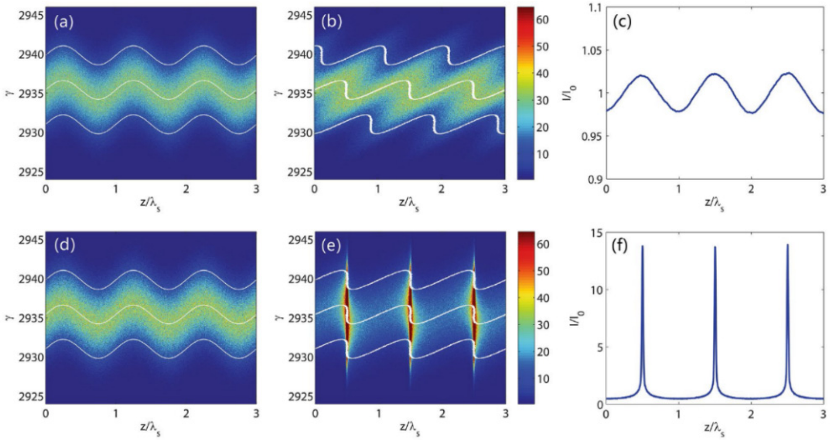
3D simulations for SR/DLSR

Elegant+Genesis, 2nd order transport effect taken into account

Main parameters used in the simulations

Parameters	Values
Beam energy	1.5 GeV
Energy spread	0.1%
Horizontal emittance	2 nm (0.2 nm for diffraction-limited SR)
Vertical emittance	2 pm
Peak current	300 A
Seed wavelength	260 nm
Modulator	80 mm×10
Seed power	200 MW
Pulse length	30 fs
Bending angle	10 mrad
Length of DS	~1 m
Radiator	30 mm×100

Longitudinal phase space evolution



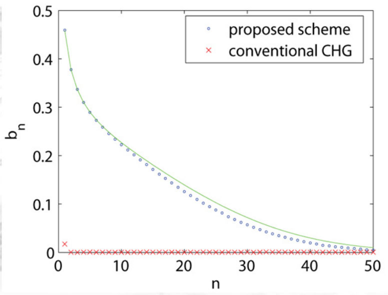
For normal CHG, the width of the current spike:

$$\Delta z = \xi \sigma_E$$

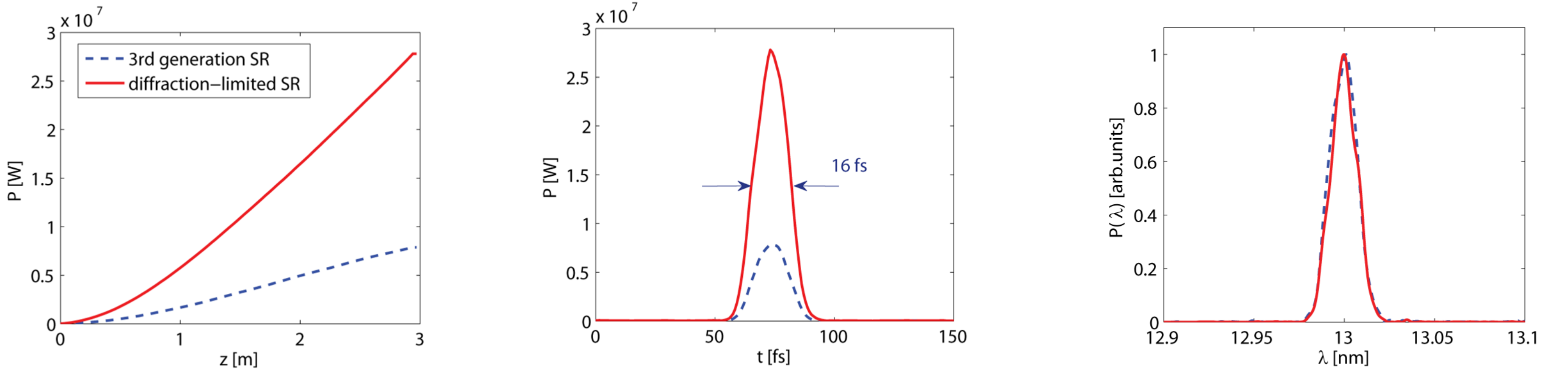
For the proposed CHG:

$$\Delta z = \eta \sigma_{y'} + (\xi - \eta b)\sigma_E$$

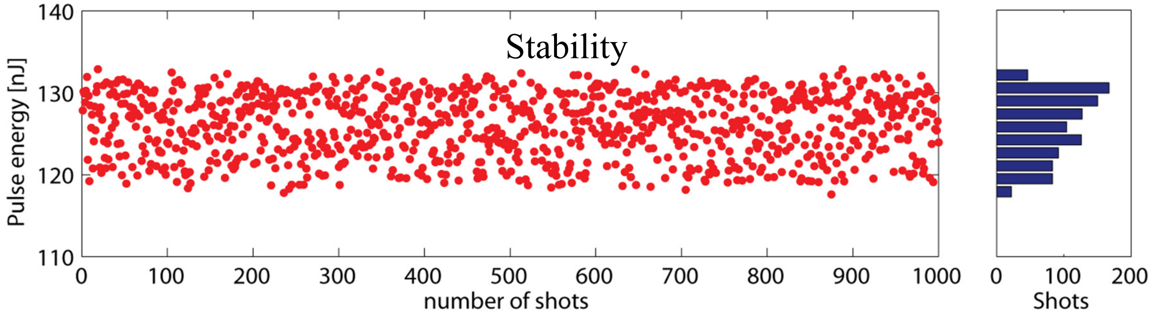
Bunching factor



3D simulations for SR/DLSR



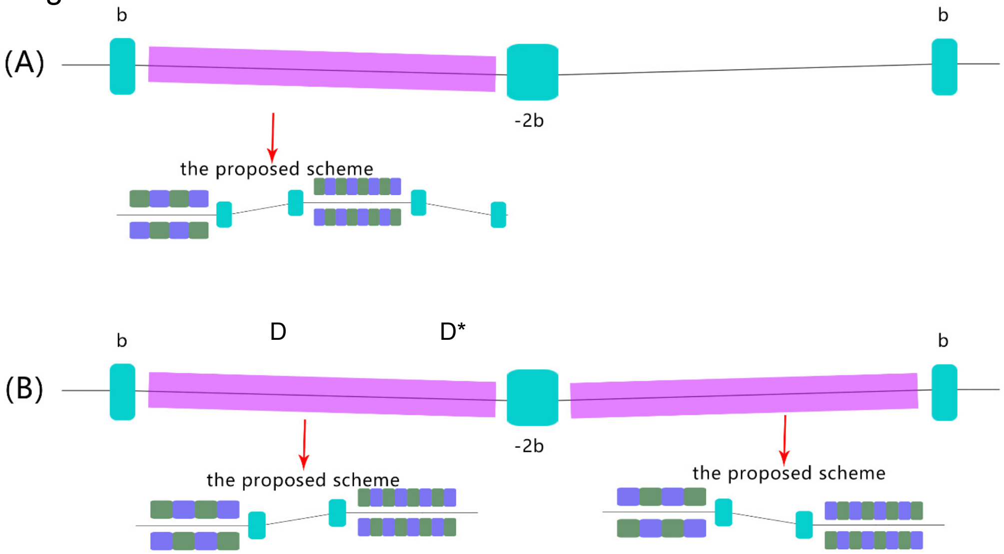
~10^{10} photons in a 16 fs pulse for normal SR



5% laser power (rms) and 0.1% magnetic field (rms) for the criteria of the laser power and the magnetic field stabilities

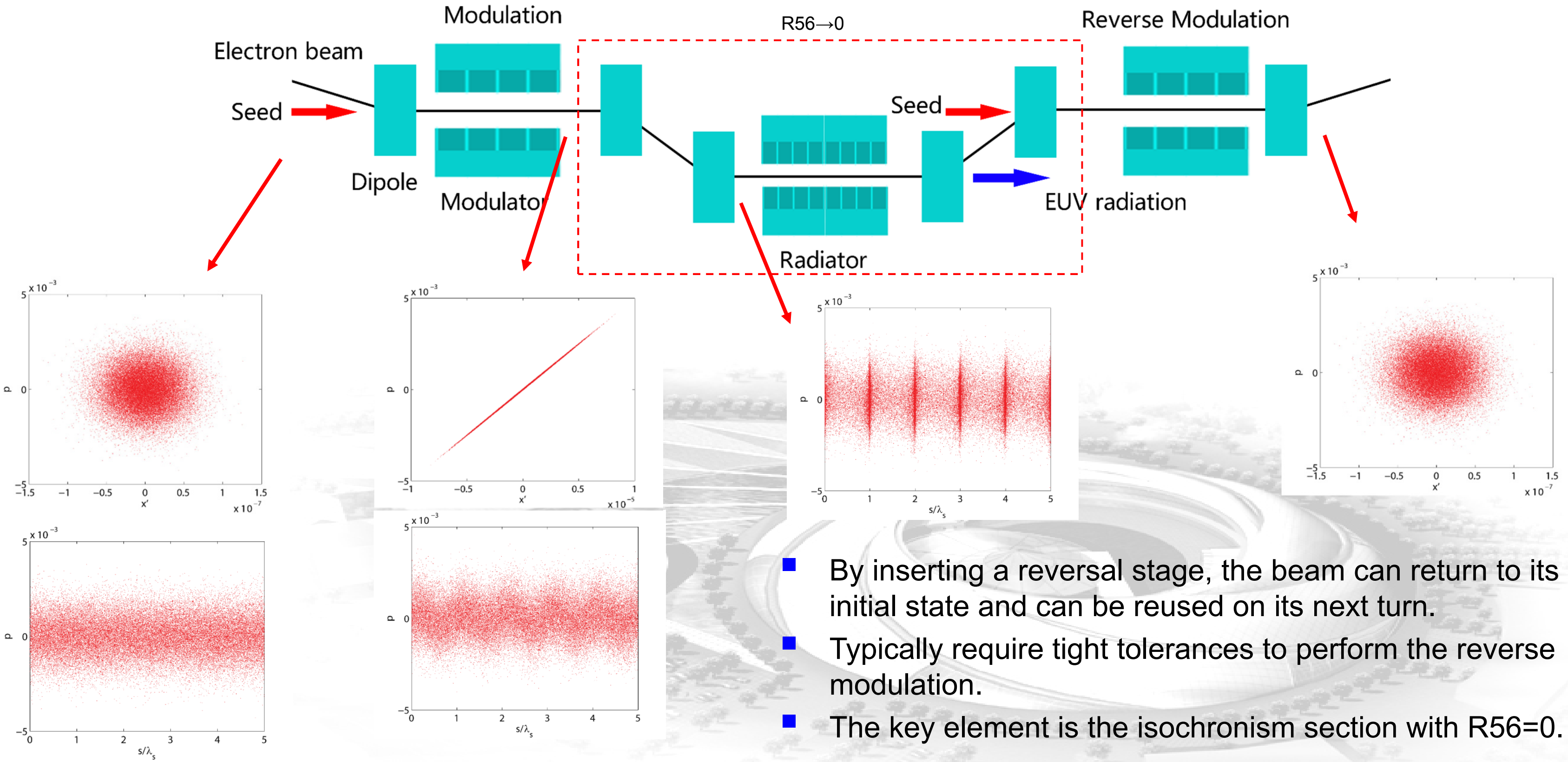
Compensate the dispersion induced by the dipoles

- One problem of the proposed scheme is the transverse dispersion induce by the dipoles.
- The dispersion induced by the dogleg can be fully compensated by another reversed dogleg (D*) after the radiator.
- The dispersion induced by the first dipole can be corrected by another two dipoles with bending angles of -2b and b elsewhere in the ring.



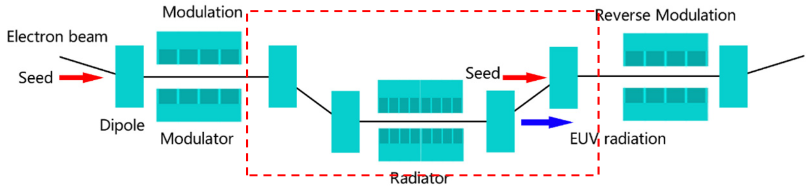
Two possible lattices in the long drift section of SR

Reversible seeding for SSMB with the proposed technique



- By inserting a reversal stage, the beam can return to its initial state and can be reused on its next turn.
- Typically require tight tolerances to perform the reverse modulation.
- The key element is the isochronism section with R56=0.

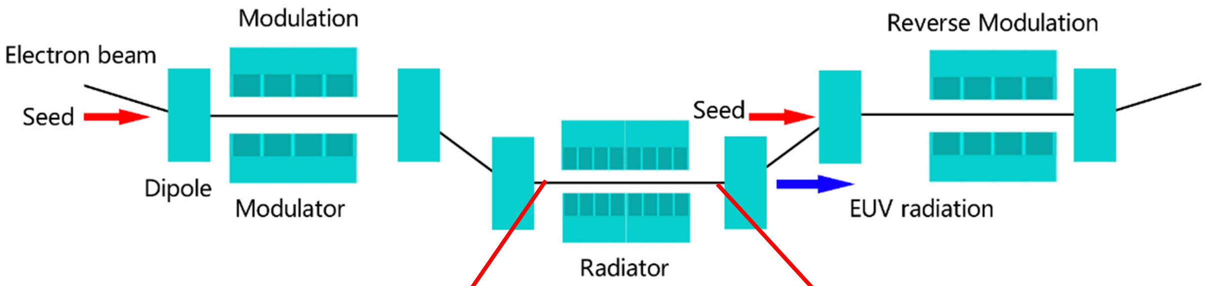
3D simulations for the reversible seeding scheme

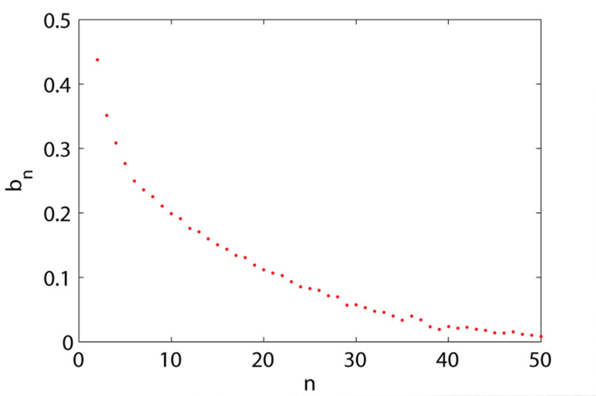


- Assuming we already have a perfect isochronism chicane
- Find the limitation of the proposed technique for SSMB

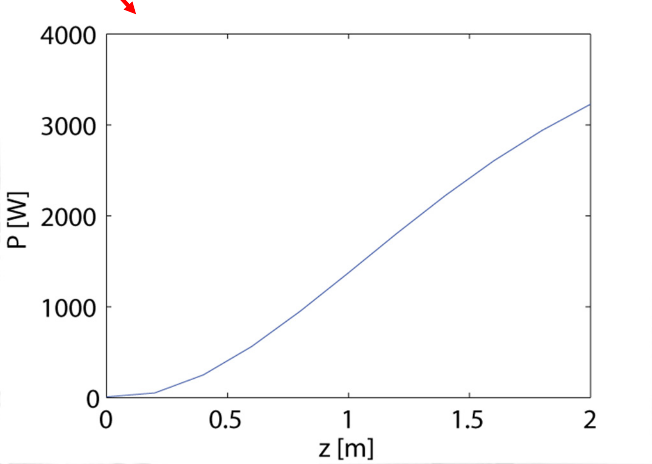
Parameters	Values
Circumference	200 m
Beam energy	1.2 GeV
Energy spread	0.1%
Horizontal emitance	2 nm-rad
Coupling parameter	0.1%
Bunch length	30 ps
Damping time (H, V, E)	11.4, 17.4, 11.9 ms
Seed wavelength	270 nm
Seed power	50 MW
Radiation wavelength	13.5 nm (20^{th} harmonic)

3D simulations for the reversible seeding scheme



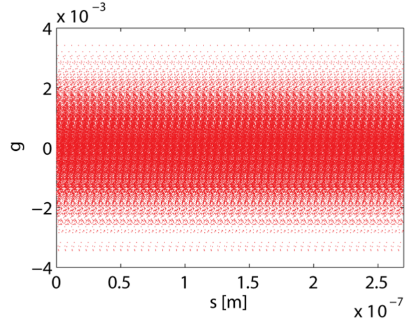


Bunching factor @ radiator entrance

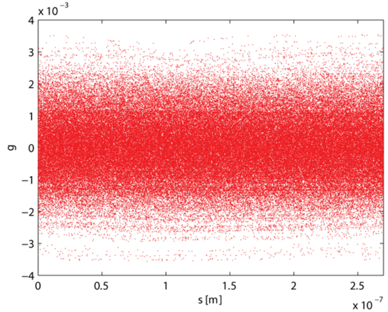


Gain curve in radiator (average power)

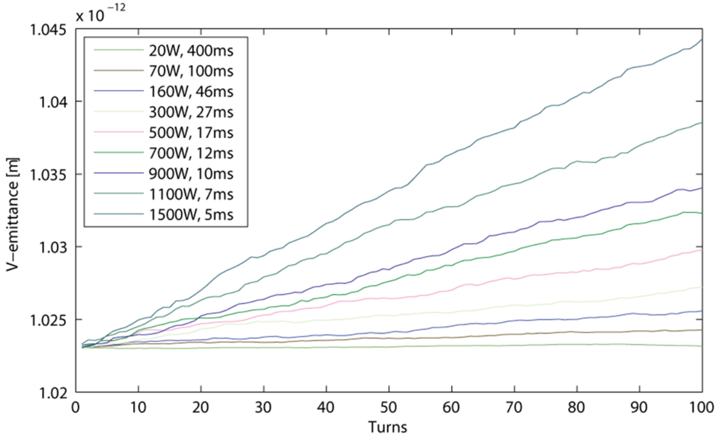
3D simulations for the reversible seeding scheme



Initial longitudinal phase space

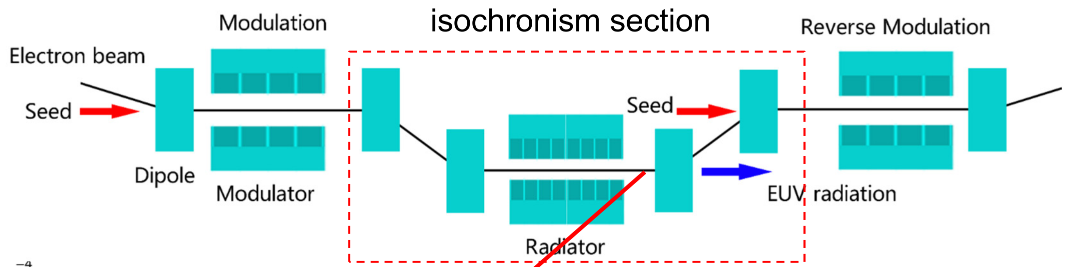


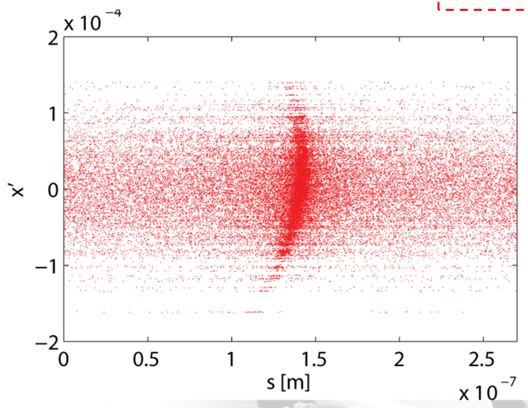
longitudinal phase space after 1000 turns

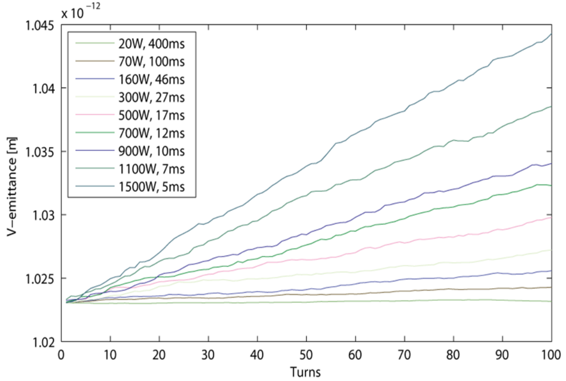


Vertical emittance growth for different average output power and corresponding growth time, for high output peak power, the longitudinal phase space is significantly changed after the radiator

Requirements for the electron beam and lattice design







The second order transport effect

- Need an electron beam with very small transverse emittance.
- The lattice for the reverse section should be properly designed to reduce the second order transport effect

Summary

- The proposed technique can fully take advantages of the small vertical angular divergence and avoid the disadvantages of large energy spread of the electron beam in SR.
- A preliminary design has been given to show the possible performance of a reversible seeding schemes based on the proposed scheme.
- Design of a reversible section with short length is the key for reducing the second order transport effects .
- Studies on the real lattice design for SSMB considering various 3D effect is still ongoing.

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Thanks!!!