ERL Based Multi-pointing Fully Coherent Light Source

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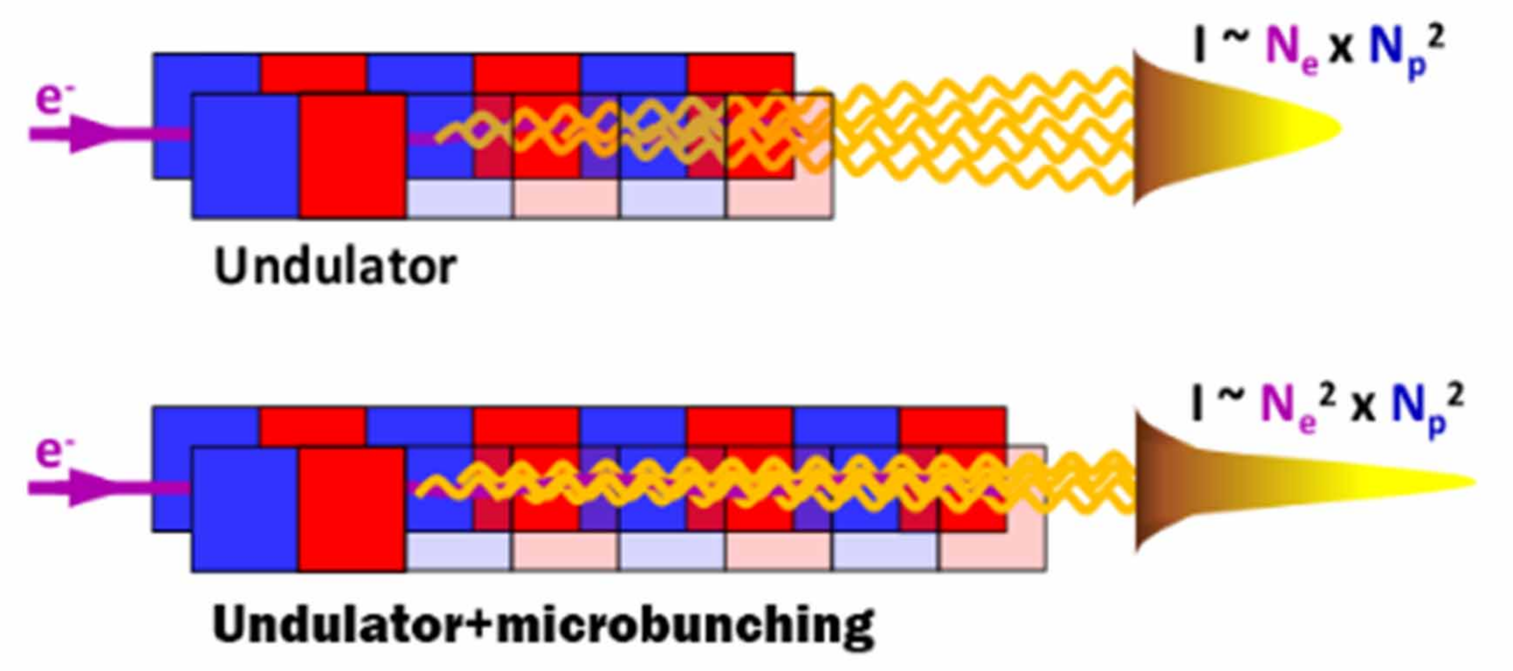
67th ICFA Beam Dynamics Workshop on Future Light Source

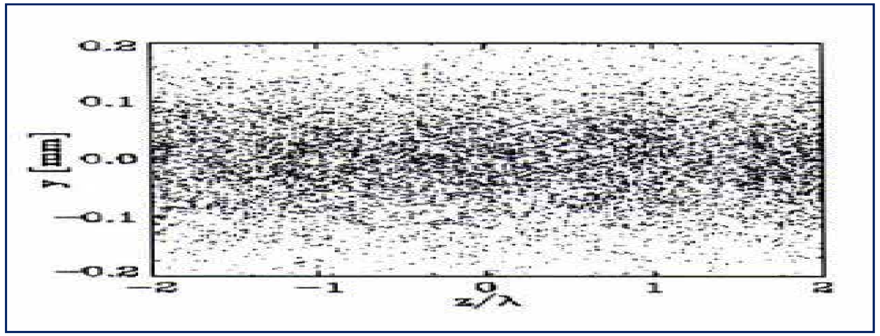
August 30th, 2023

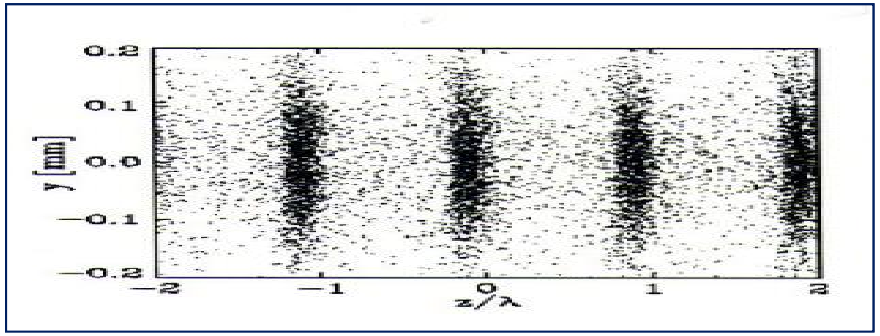
outline

- From SR to fully coherent radiation
  - Coherent harmonic generation
  - Echo-enabled harmonic generation
  - Angular dispersion induced microbunching
  - Reversible modulation
- An ERL Light Source for Coherent Radiation
  - ADM + ERL
  - high-flux mode and high-resolution mode
- Multi-pointing system
  - Large angle bending system
  - 5 times radiation
- Two Further Considerations on ADM based ERL
  - 3GeV single turn ERL
  - 1.5GeV double-turn ERL
- Summary

From SR to fully coherent radiation



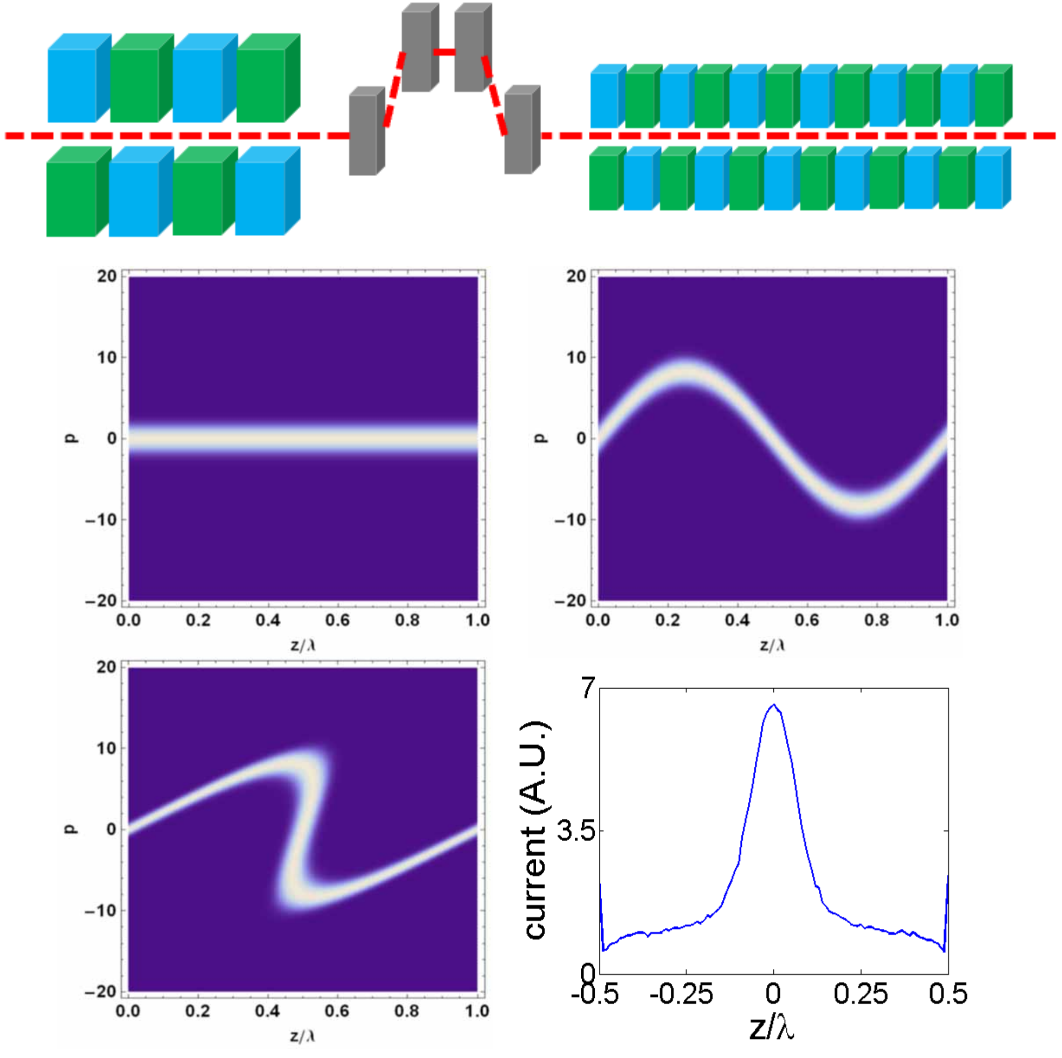




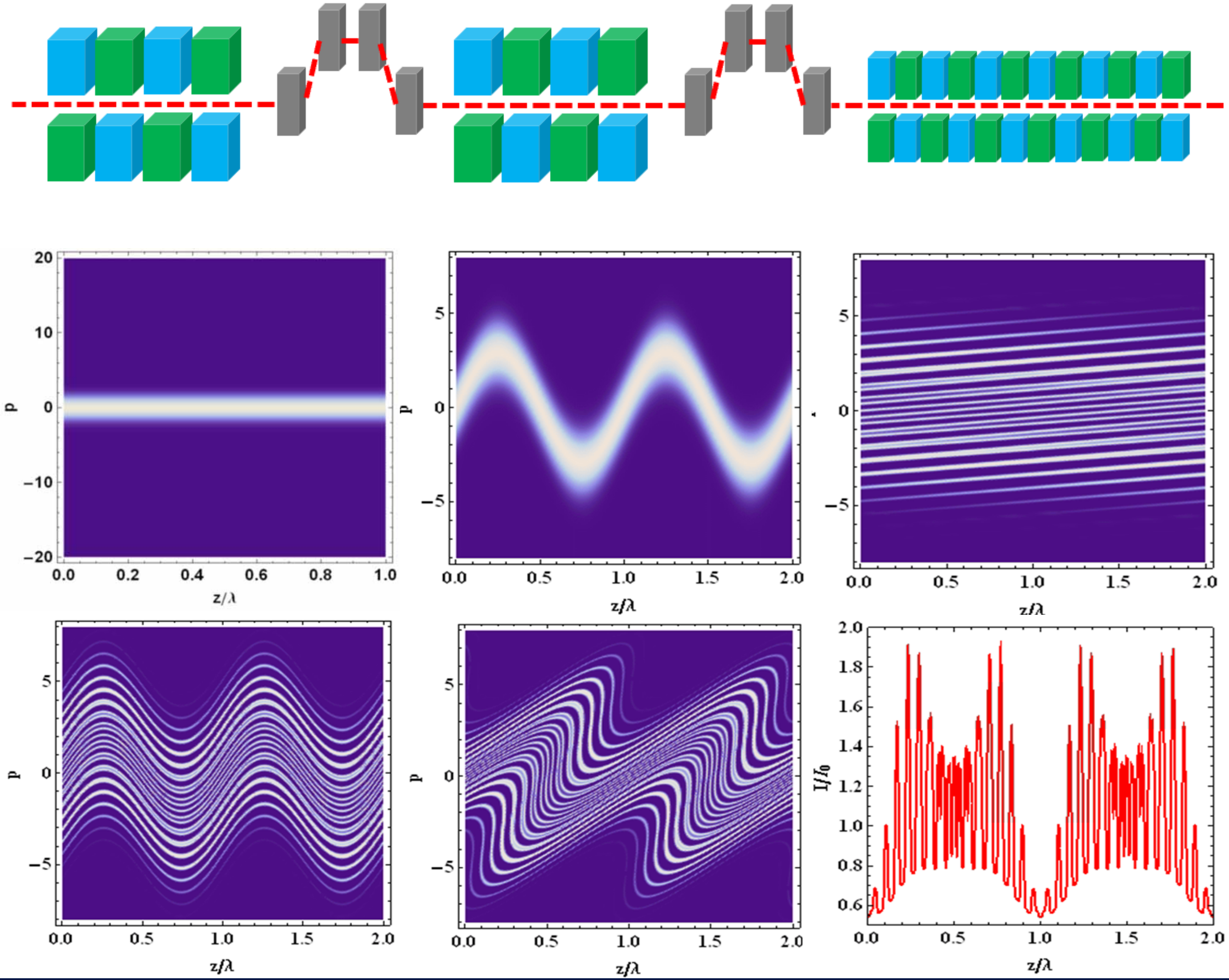
- ➢Synchrotron Radiation is incoherent with random distribution beam
- ➢Fully coherent radiation is the SR with microbunched beam
- ➢The key to generate microbunching is to modulate the beam with seed laser

How to generate microbunching

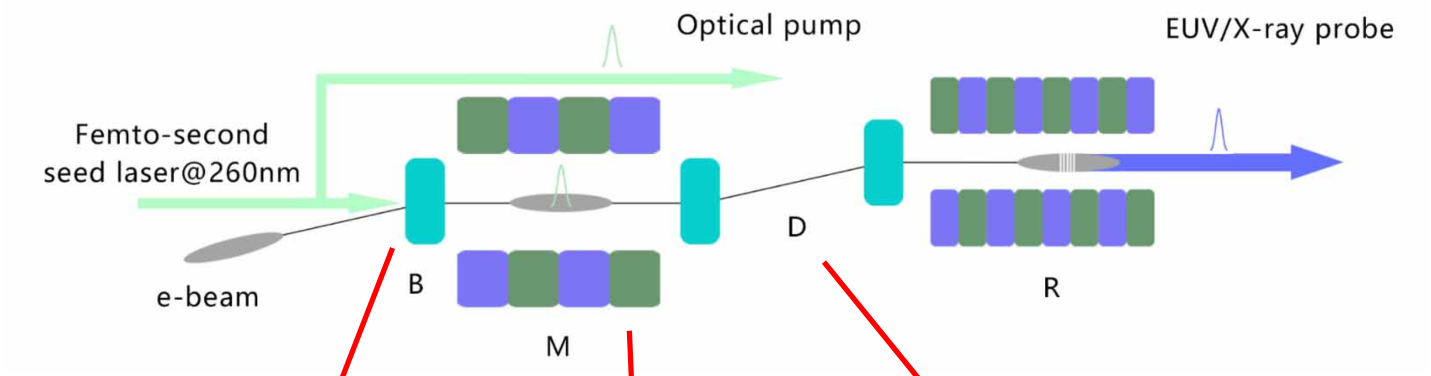
Coherent Harmonic Generation



Echo-enabled Harmonic Generation



Angular dispersion induced microbunching



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

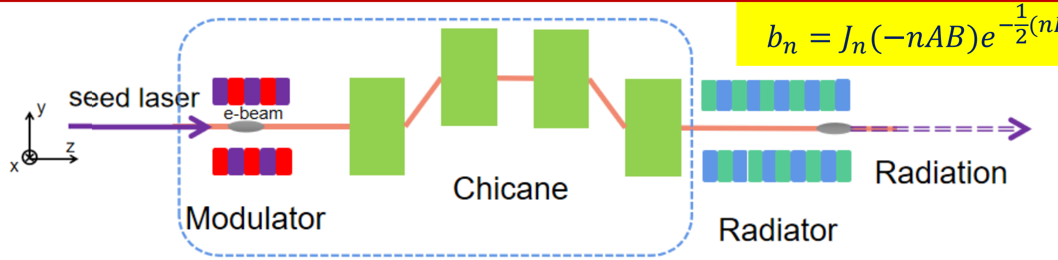
$$R = R_D \cdot R_M \cdot R_B = \begin{pmatrix} 1+hb\eta & L & h\eta & \eta-(L-L_b)b \\ 0 & 1 & 0 & -b \\ b(1+h\xi) & \eta & 1+h\xi & \xi-\eta b \\ hb & 0 & h & 1 \end{pmatrix}$$

$$1+h\xi_D = 0, \quad \xi-\eta b = 0 \Rightarrow b_n = J_n\left(nk_s\xi\frac{\Delta\gamma}{\gamma}\right)e^{-\frac{1}{2}(nk_s\eta\sigma_{y'})^2}$$

- Bunching factor is determined by the initial y’
- Lattice is relative simple
- Energy modulation can be much smaller than the initial energy spread, which means very low laser power is required → High rep-rate seed laser with current available technology

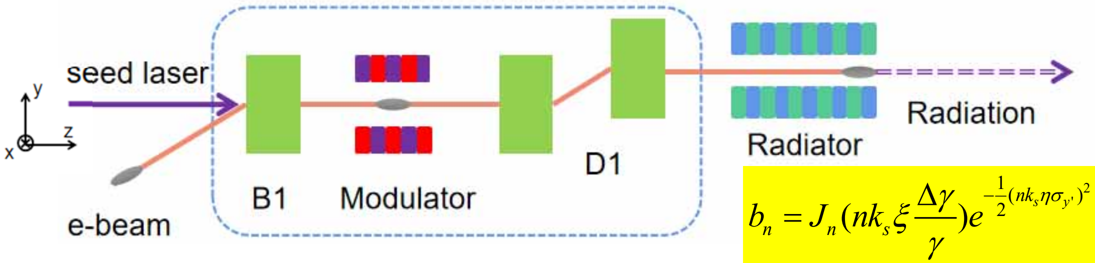
Chao Feng, Zhentang Zhao, Scientific reports, 7, 4724 (2017)

Coherent radiation scheme: CHG vs ADM



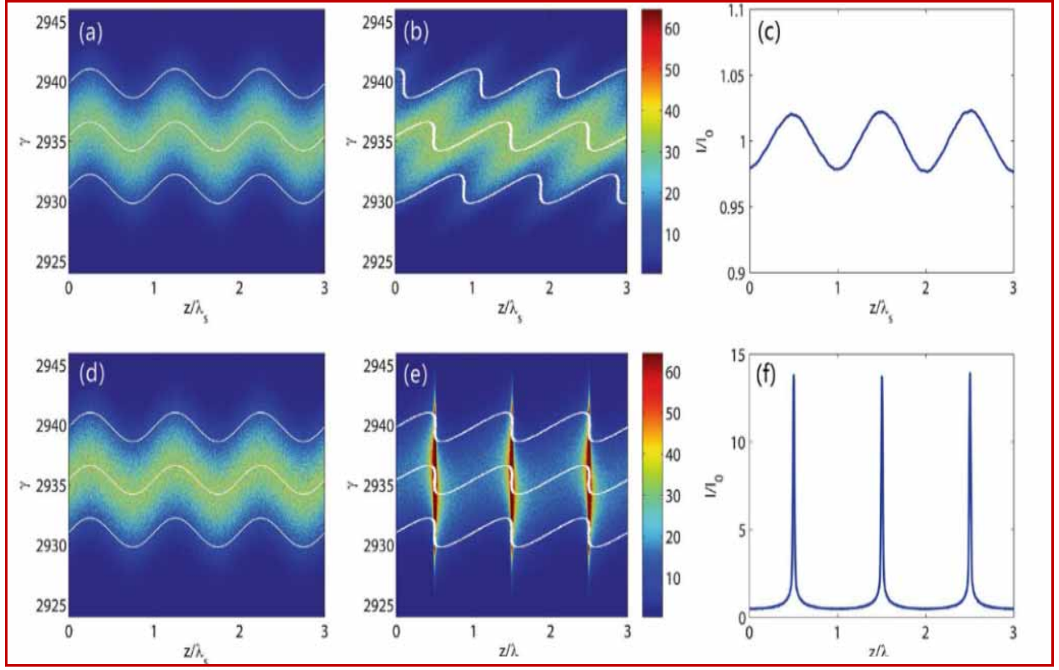
$$b_n = J_n(-nAB)e^{-\frac{1}{2}(nB)^2}$$

Coherent Harmonic Generation (CHG)



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

Angular-Dispersion induced Microbunching (ADM)

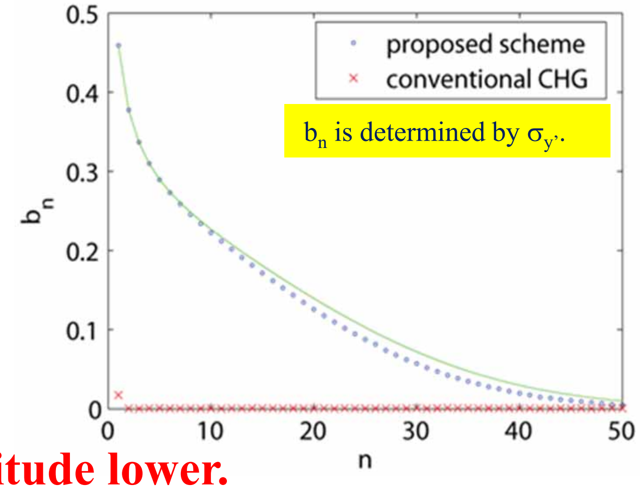


For the normal CHG, the width of the current spike:

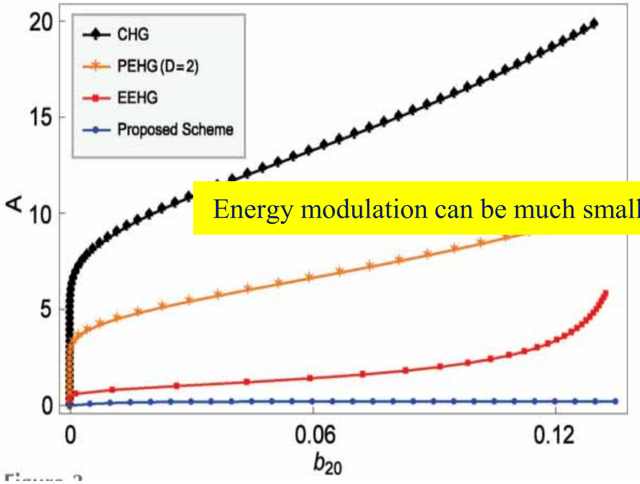
$$\Delta z = \xi\sigma_E$$

For the ADM:

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



b_n is determined by $\sigma_{y'}$.

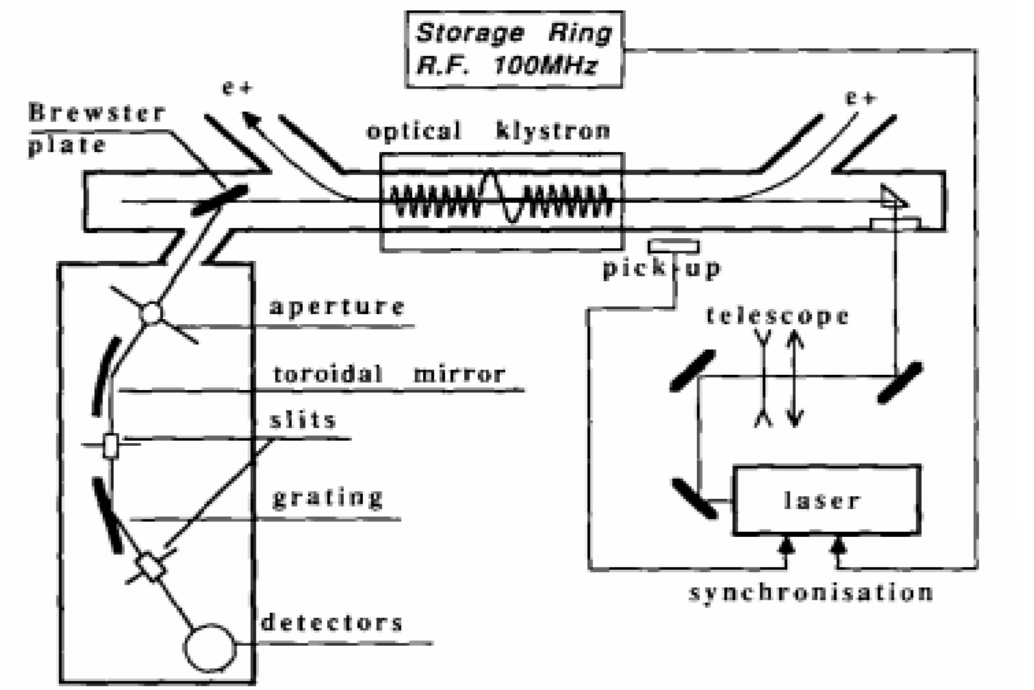


Energy modulation can be much smaller

Requirement on the seed laser is 3 orders of magnitude lower.

Storage ring based coherent radiation

Coherent Harmonic Generation

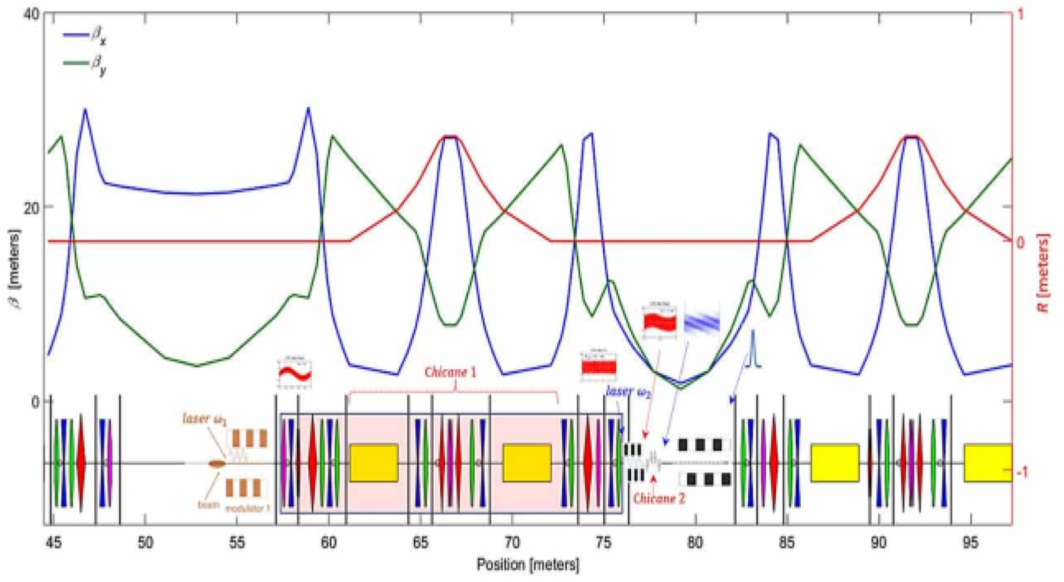


Coherent harmonic generation in VUV with the optical klystron on the storage ring Super-ACO

R. Prazeres [a], P. Guyot-Sionnest [a], J.M. Ortega [a,b], D. Jaroszynski [a,c], M. Billardon [a,b], M.E. Couprie [a,c], M. Velghe [a,d] and Y. Petroff [a]

[a] LURE, CNRS/CEA/MEN, bât 209d, Université de Paris-sud, 91405 Orsay cedex, France
[b] Ecole Supérieure de Physique Chimie, 10 rue Vauquelin, 75231 Paris, France
[c] CEA/DSM/DPhG/SPAS, CEN Saclay, 91191 Gif-sur-Yvette, France
[d] LPPM, Université de Paris-sud, 91405 Orsay cedex, France

Echo-enabled Harmonic Generation



scientific reports

Check for updates

OPEN

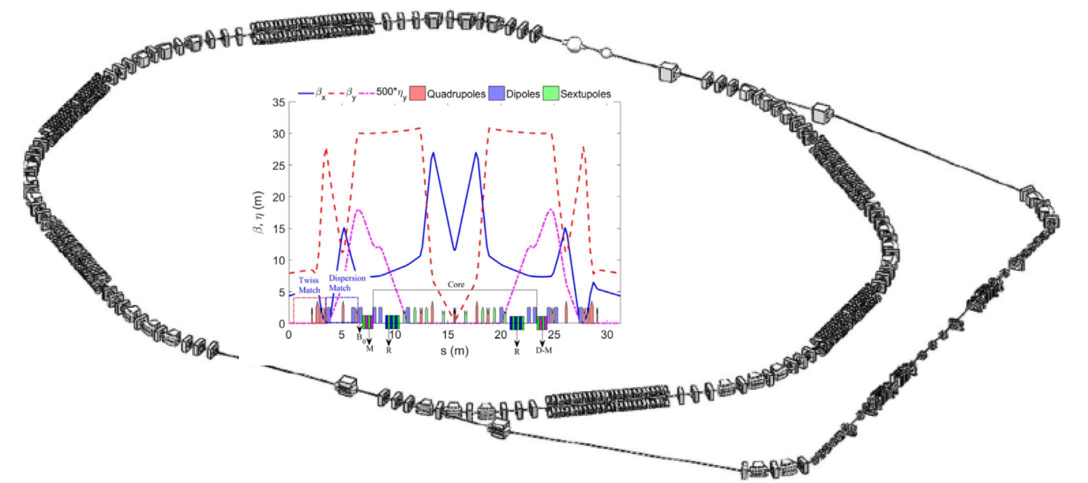
Optimization of echo-enabled harmonic generation toward coherent EUV and soft X-ray free-electron laser at NSLS-II

X. Yang[1], G. Penn[2], L. H. Yu[1], V. Smaluk[1] & T. Shaftan[1]

Challenge: high requirement for seed laser and energy spread degradation

Storage ring based coherent radiation

Angular-Dispersion Microbunching



SCIENTIFIC REPORTS

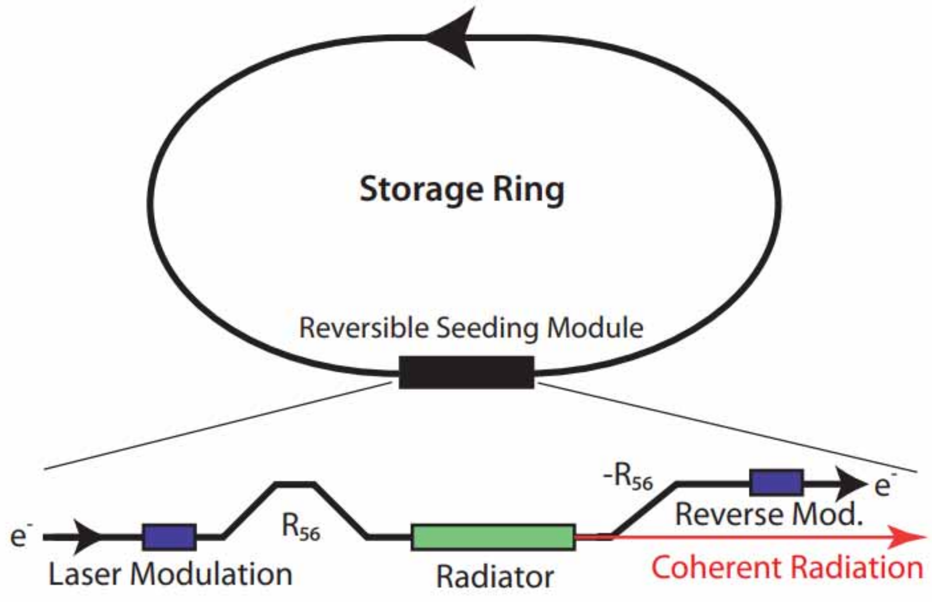
OPEN A Storage Ring Based Free-Electron Laser for Generating Ultrashort Coherent EUV and X-ray Radiation

Check for updates

OPEN A synchrotron-based kilowatt-level radiation source for EUV lithography

Bocheng Jiang[1,2], Chao Feng[1,2✉], Changliang Li[1], Zhenghe Bai[3], Weishi Wan[4], Dao Xiang[5], Qiang Gu[1,2], Kun Wang[1,2,6], Qinglei Zhang[1], Dazhang Huang[1,2] & Senyu Chen[7]

Modulation anti-Modulation



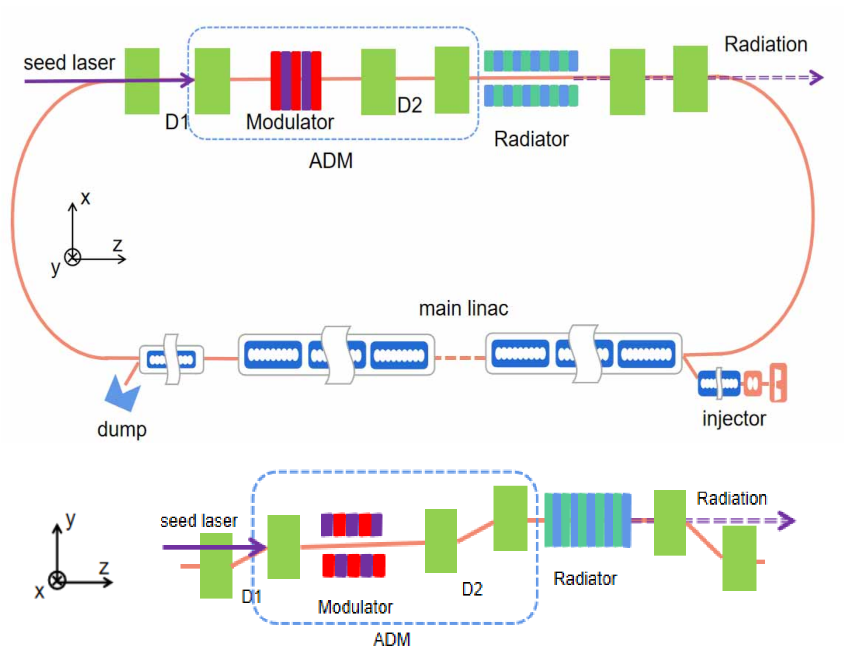
Proceedings of FEL2011, Shanghai, China

REVERSIBLE SEEDING IN STORAGE RINGS

Daniel Ratner* and Alex Chao, SLAC, Menlo Park, California, USA

Challenge: sensitive to the lattice and scheme complex

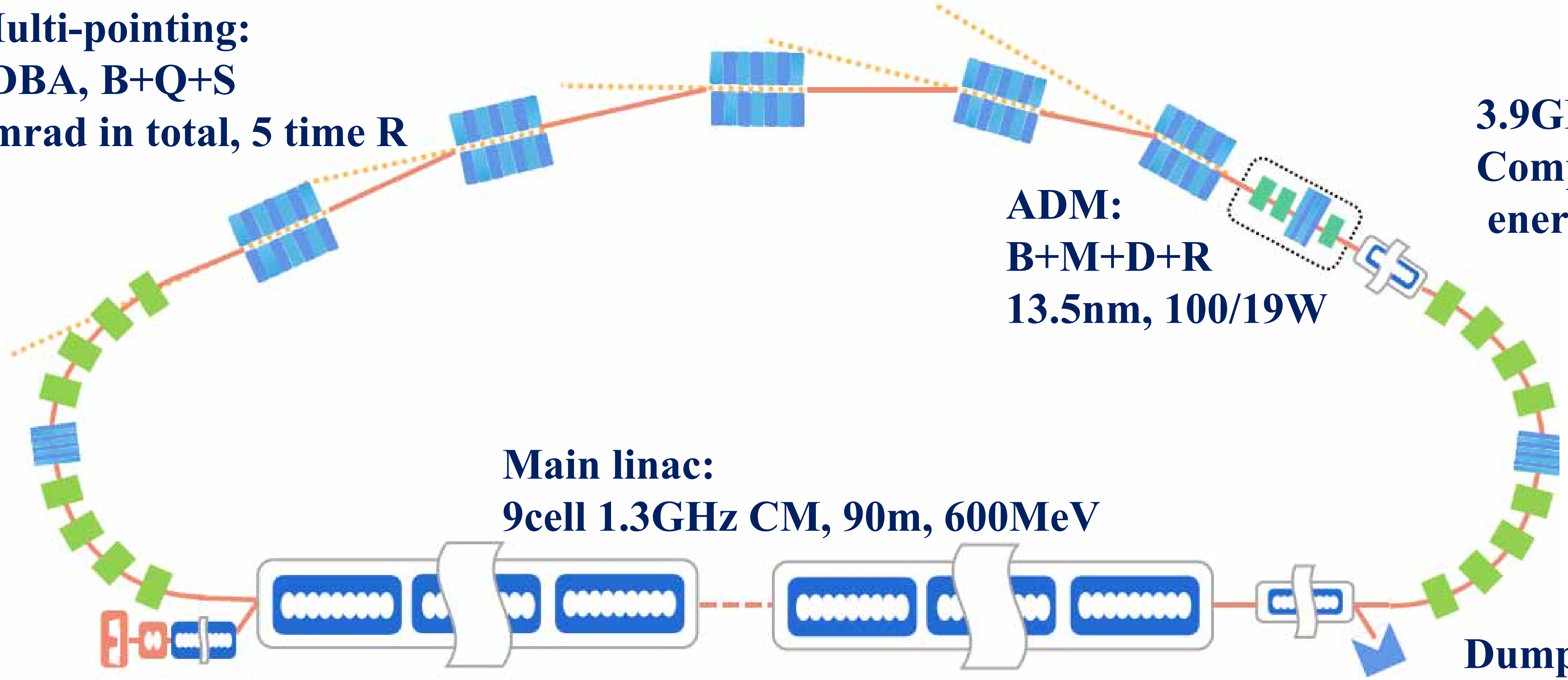
Novel concept: ADM + ERL



- Merits of ERL:
  - High quality electron beams with R2F
  - Always fresh electron beam
  - High repetition rate
- Demerit of ERL
  - Low achievable average current (tens of mA) and peak current (<100A), so no high-gain at short wavelength
- Reasons for Implementing ADM on ERL
  - Less requirements of ADM on the seed laser power and electron beam current
  - Generate high repetition rate, high average brilliance and fully coherent pulse

- **The brightness of ERL with ADM would be over 10^{25} (phs/s/mm²/mrad²/0.1%BW), which is $10^{3\sim4}$ times higher than that of DLSR with the same beam energy**
- **The average power can be over 100W at 13.5 nm**

ERL based multi-pointing fully coherent light source



Multi-pointing:
4DBA, B+Q+S
8mrad in total, 5 time R

3.9GHz CM:
Compensate
energy chirp

ADM:
B+M+D+R
13.5nm, 100/19W

180° arc:
Preserve beam
quality, compression

Main linac:
9cell 1.3GHz CM, 90m, 600MeV

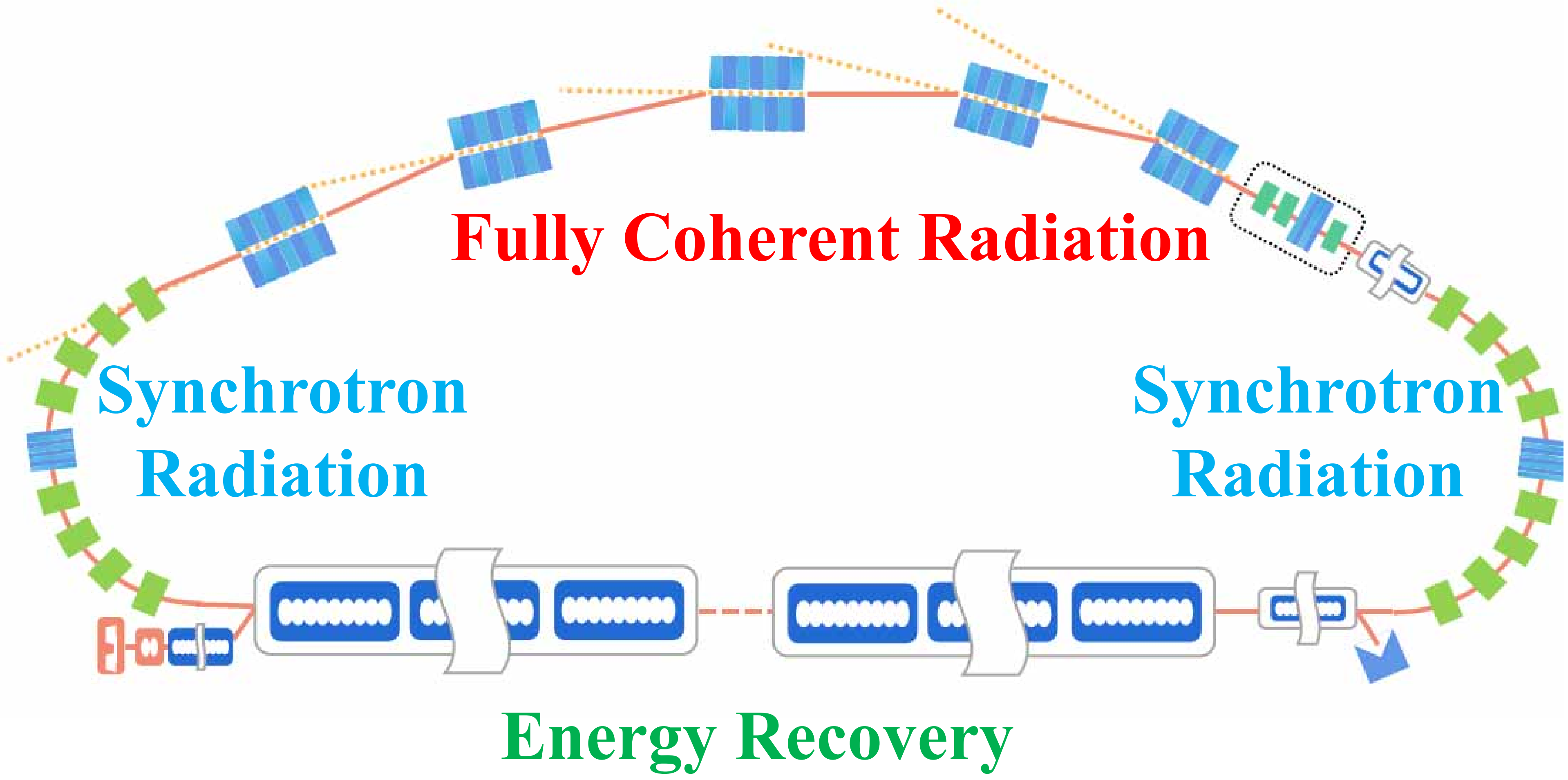
Dump:
Energy recovery(97%)

Injector:
DCgun+buncher+2cell CM
77pC, 0.5um, 15A, 15MeV

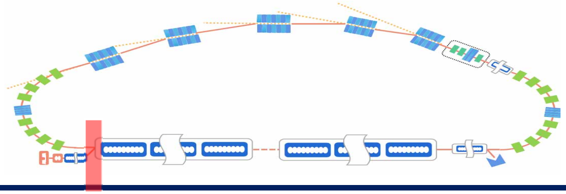
R2F:
Skew quadrupole
0.5um => 5/0.05um

3.9GHz CM:
Compensate nonlinear
energy spread

ERL based multi-pointing fully coherent light source



Round to flat technique (R2F)



- Flat electron beams:
  - Beams with large transverse emittance ratios
  - Enhance the microbunching of ADM
- Generate a flat beam directly out of a photoinjector:
  - Immerse the photocathode in an axial magnetic field to generat a magnetized beam.
  - After acceleration, use three skew quadrupole to transform the beam into a flat beam.

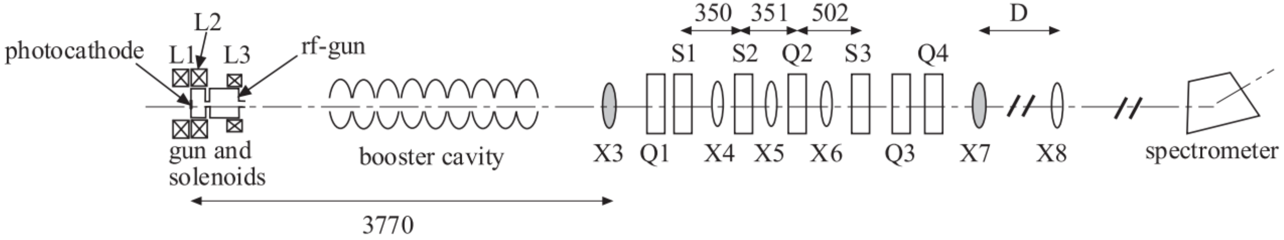
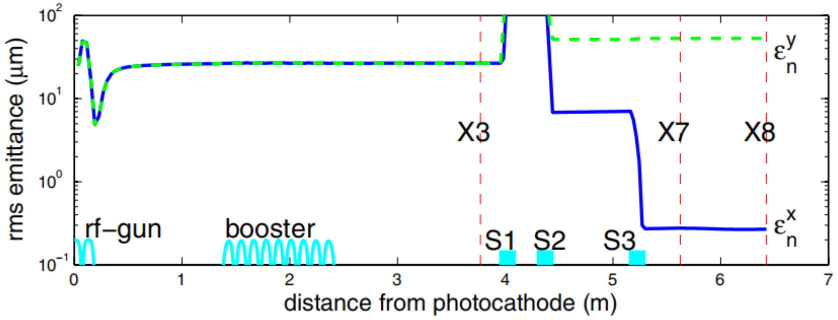


FIG. 1. Overview of the Fermilab/NICADD photoinjector. "X" refer to diagnostics stations (beam viewers, and/or slit location), "L" to the solenoidal lenses, "Q" to quadrupoles, and "S" to the skew quadrupoles. All distances are in mm, with $D = 800$ (or 1850 for the data presented in Fig. 7).

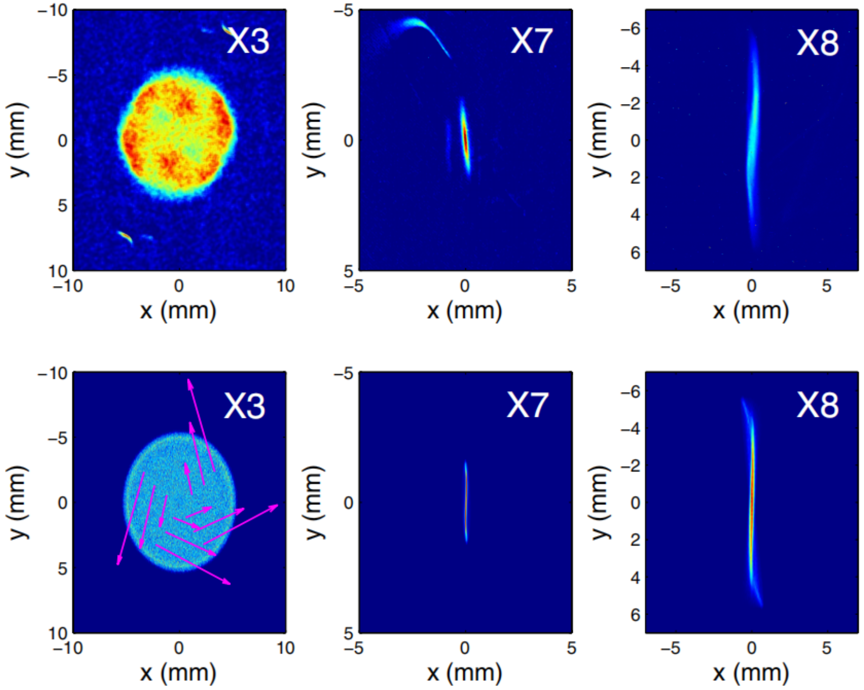
$$\varepsilon_n^{\pm} = \sqrt{(\varepsilon_n^u)^2 + (\beta\gamma\mathcal{L})^2}$$

$$\pm (\beta\gamma\mathcal{L}) \overset{\beta\gamma\mathcal{L} \gg \varepsilon_n^u}{\longrightarrow} \begin{cases} \varepsilon_n^+ \simeq 2\beta\gamma\mathcal{L}, \\ \varepsilon_n^- \simeq \frac{(\varepsilon_n^u)^2}{2\beta\gamma\mathcal{L}}, \end{cases}$$

the normalized uncorrelated emittance of the magnetized beam prior to the transformer



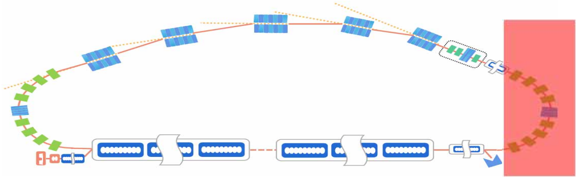
Evolution of beam normalized emittances along the beam line

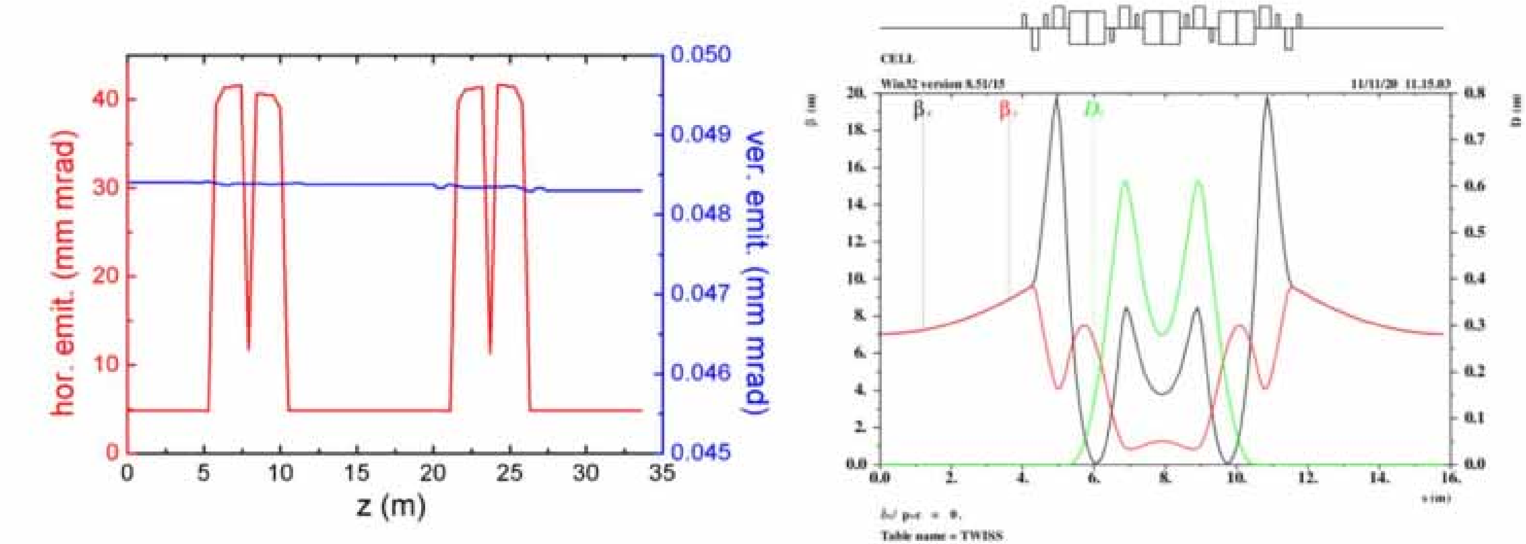


Example of the transformation of the incoming angular-momentum-dominated round beam into a flat beam.
Top row: measurements; bottom row: corresponding numerical simulations.

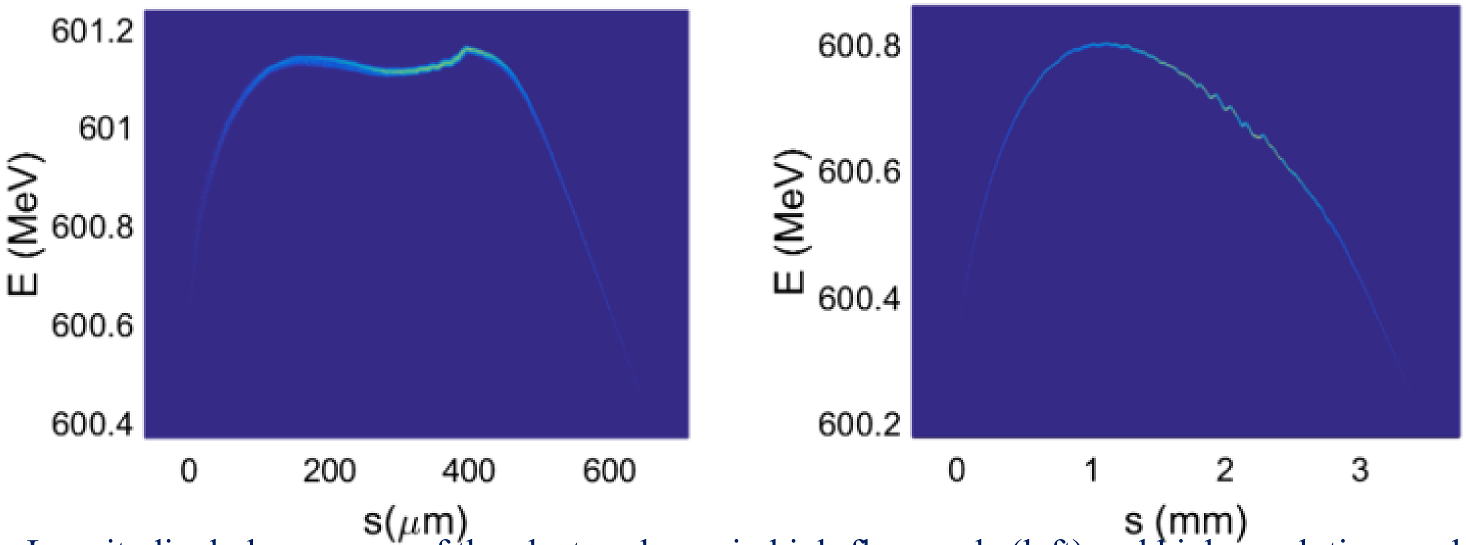
Piot, P., Sun, Y.-E. & Kim, K.-J. Photoinjector generation of a fat electron beam with transverse emittance ratio of 100. Phys. Rev. ST Accel. Beams 9, 031001. https://doi.org/10.1103/PhysRevSTAB.9.031001 (2006).

Lattice for the Arc





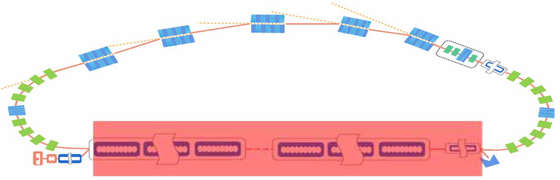
Emittances evolution of the half arc(left) and the layout and optical function of one TBA cell(right).



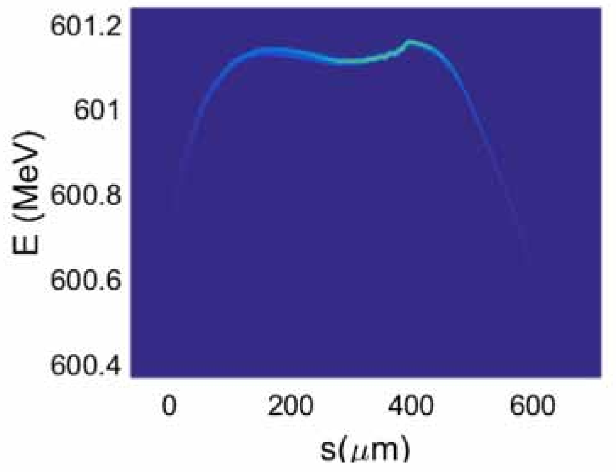
Longitudinal phase space of the electron beam in high-flux mode (left) and high-resolution mode (right) at the entrance of undulator

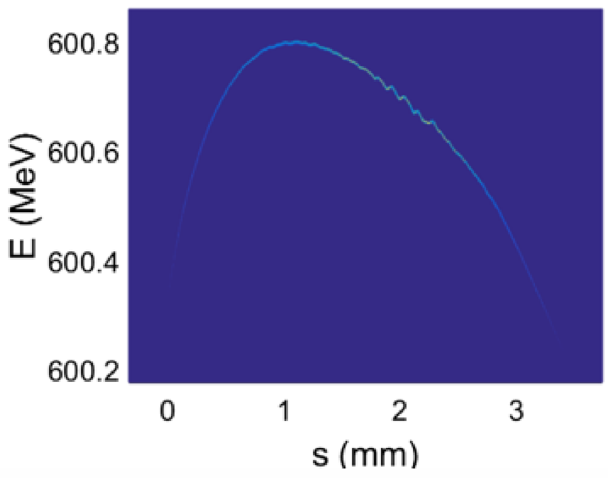
Parameters	Value	units
Energy(injector)	15	MeV
Energy(linac)	600	MeV
Nor. Emittance(injector)	0.5	μm
Nor. Emittance(linac/und.)	5/0.05	μm
Bunch charge	77	pC
Pulse duration(linac)	4	ps
Pulse duration(undulator)	0.7/4	ps
Peak current	100/15	A
Relative energy spread	0.1	%
DC gun voltage	550	kV
Repetition rate	1.3	GHz
Drive laser duration	20	ps
Drive laser spot size	0.5	mm
Bend angle in the arc	30	°

High flux & high resolution mode



- **Adjust the phase/amplitude of the linac to optimize the beam energy chirp, the beam will be compressed in the arc section.**



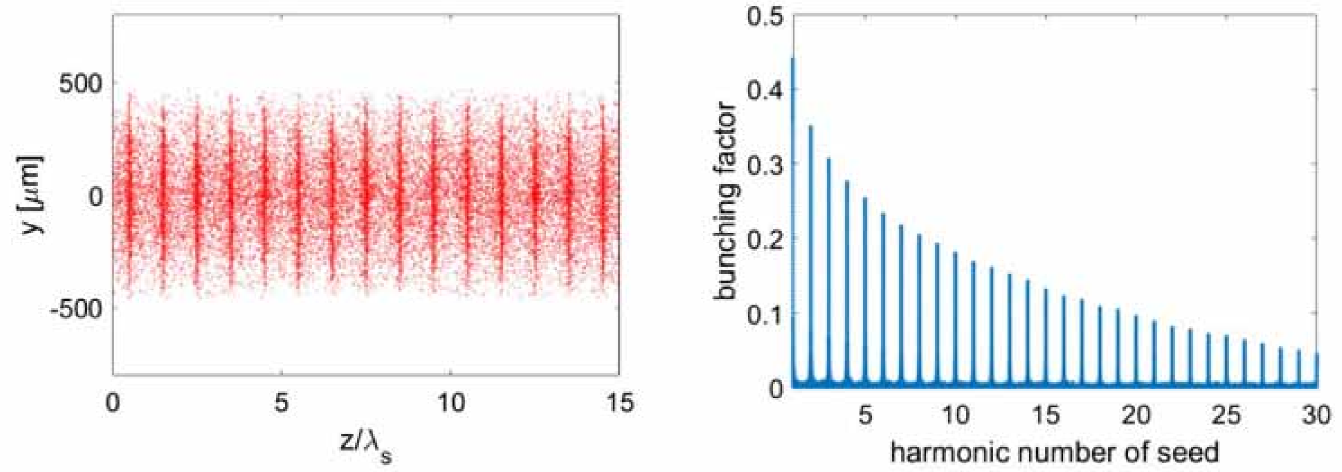


high flux mode

High peak current (100A, 0.7ps)

high resolution mode

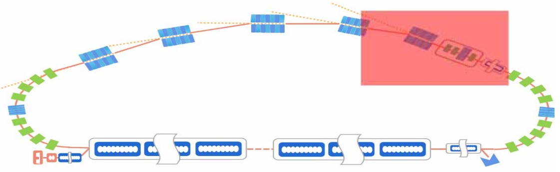
Long pulse duration (15A, 4ps)

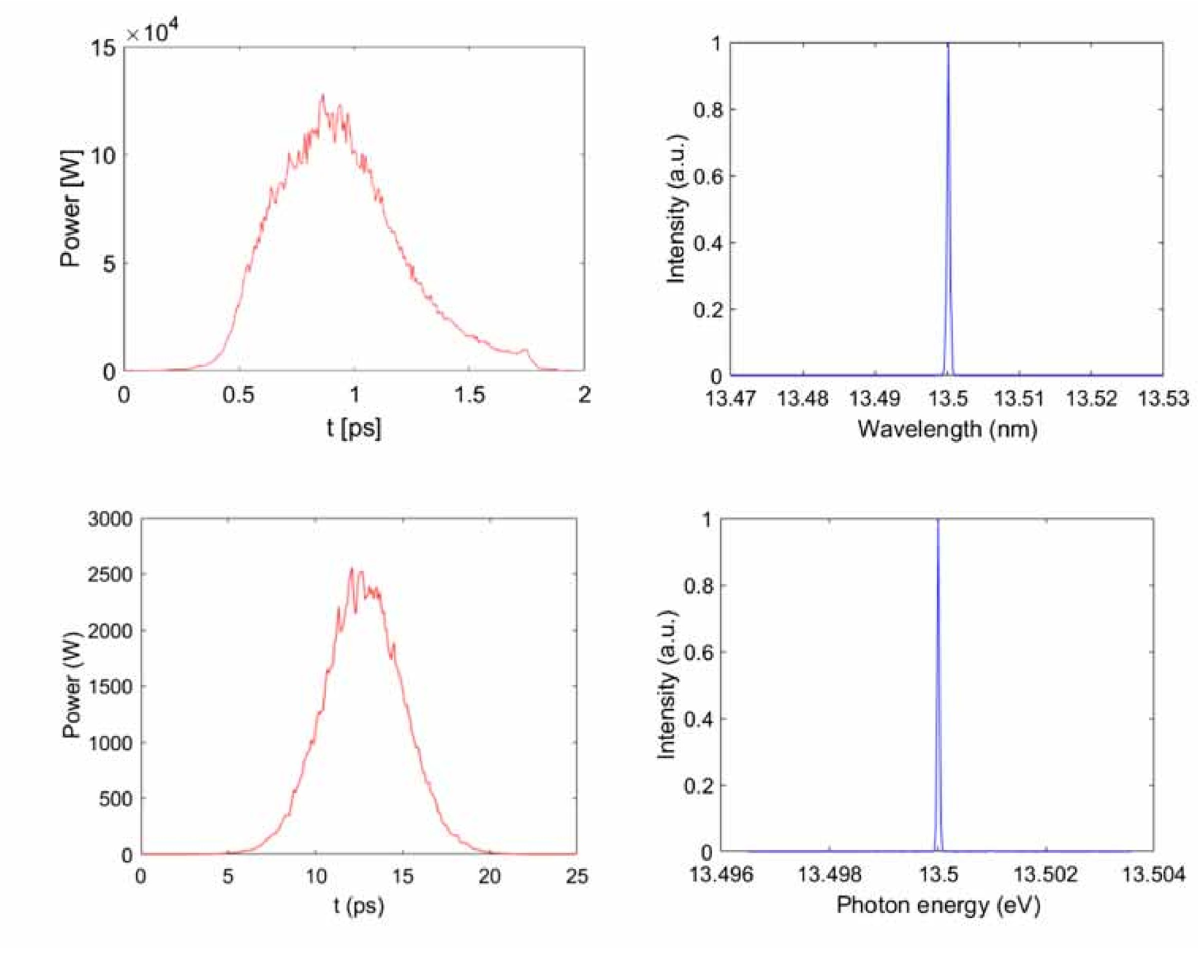


density modulation and bunching factors at various harmonics of the seed laser

~257nm seed laser from forth harmonic generation of the fiber laser

High flux & high resolution mode





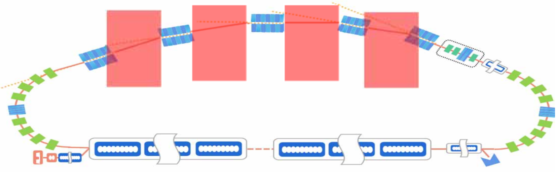
Radiation pulses and spectra at the exit of the radiator with high-flux mode (up) and high-resolution mode (down).

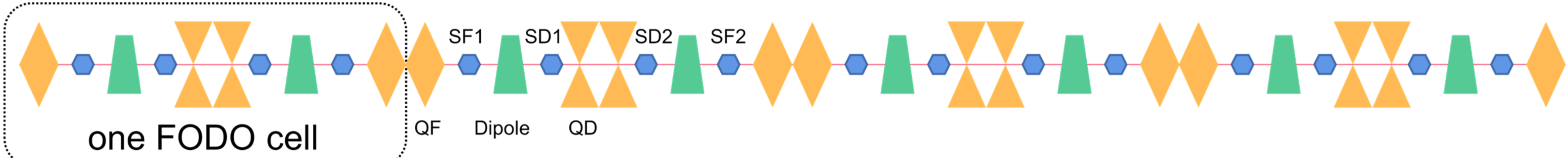
- **high-flux mode (suitable for EUV lithography)**
  - peak power: 120kW
  - spectral bandwidth: 3.5meV
  - average output power: 100W
  - average brightness: 10^{25} phs/s/mm^2/mrad^2/0.1%BW

- **high-resolution mode (suitable for ARPES):**
  - radiation pulses length: 6ps
  - spectral bandwidth: 0.4meV@13.5 nm
  - average output power: 19W

Parameters	Value (high- flux/resolution mode)	Units
Bending angle	0.2	rad
Modulator period	3.5	cm
Modulator length	3	m
Radiator period	2	cm
Radiator length	3	m
Seed laser wavelength	256.5	nm
Seed laser duration	2/10	ps
Seed laser peak power	10	kW
Radiation wavelength	13.5	nm
Radiation peak power	120/2.5	kW
Radiation pulse length	0.7/6	ps
Radiation pulse energy	84/15	nJ
Average output power	100/19	W

Multi-pointing system

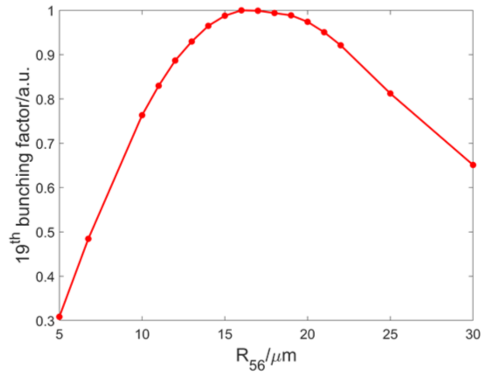




$$R_B=\begin{pmatrix} 1-\frac{\theta^2}{2} & \rho\theta & 0 & 0 & 0 & \frac{\rho\theta^2}{2} \\ -\frac{\theta}{\rho} & 1-\frac{\theta^2}{2} & 0 & 0 & 0 & \theta \\ 0 & 0 & 1 & \rho\theta & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -\theta & -\frac{\rho\theta^2}{2} & 0 & 0 & 1 & -\frac{\rho\theta^3}{6} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \quad R_{QD}=\begin{pmatrix} coshk_s & \frac{sinhk_s}{k_s} & 0 & 0 & 0 & 0 \\ k_s sinhk_s & coshk_s & 0 & 0 & 0 & 0 \\ 0 & 0 & cosk_s & \frac{sink_s}{k_s} & 0 & 0 \\ 0 & 0 & -k_s sink_s & cosk_s & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix},$$

$$R_{QF}=\begin{pmatrix} cosk_s & \frac{sink_s}{k_s} & 0 & 0 & 0 & 0 \\ -k_s sink_s & cosk_s & 0 & 0 & 0 & 0 \\ 0 & 0 & coshk_s & \frac{sinhk_s}{k_s} & 0 & 0 \\ 0 & 0 & k_s sinhk_s & coshk_s & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \quad R_D=\begin{pmatrix} 1 & l & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & l & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix},$$

Parameter	Value	Units
bend length	0.15	m
bend angle	1	mrad
Quadrupole length	0.15	m
QF strength	3.785	$1/m^2$
QD strength	-3.785	$1/m^2$
Sextupole length	0.25	m
SF1 strength	1042	$1/m^3$
SF2 strength	1346	$1/m^3$
SD1 strength	-2968	$1/m^3$
SD2 strength	-682	$1/m^3$
R_{56}	19.5	μm
T_{566}	14.8	μm



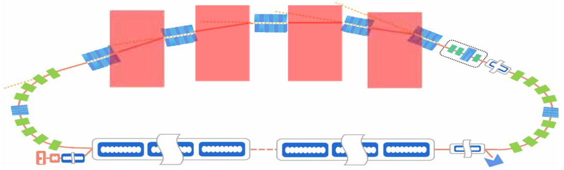
$$T_{226}=-T_{116}=T_{512}=0, \quad T_{446}=-T_{336}=T_{534}=0,$$

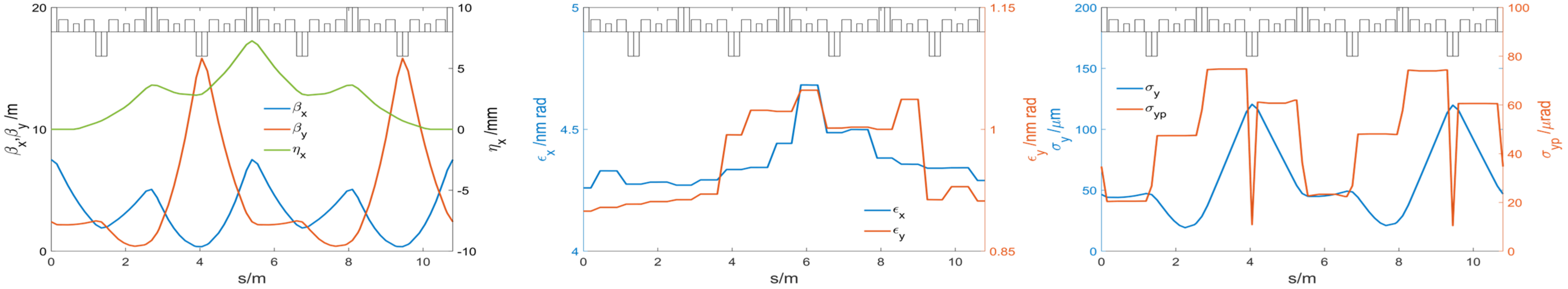
$$T_{216}=2T_{511}, \quad T_{126}=-2T_{522},$$

$$T_{436}=2T_{533}, \quad T_{346}=-2T_{544},$$

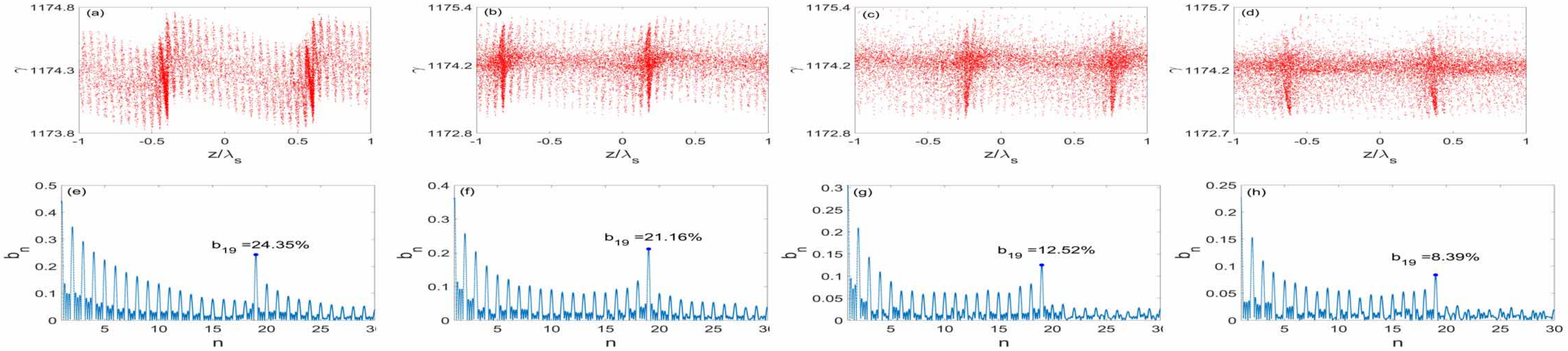
$$T_{516}=2T_{266}, \quad T_{526}=-2T_{166}.$$

Multi-pointing system



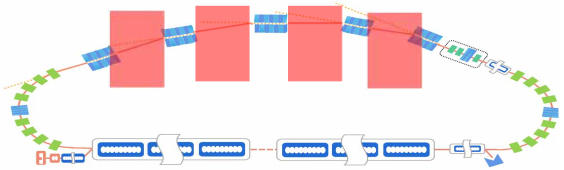


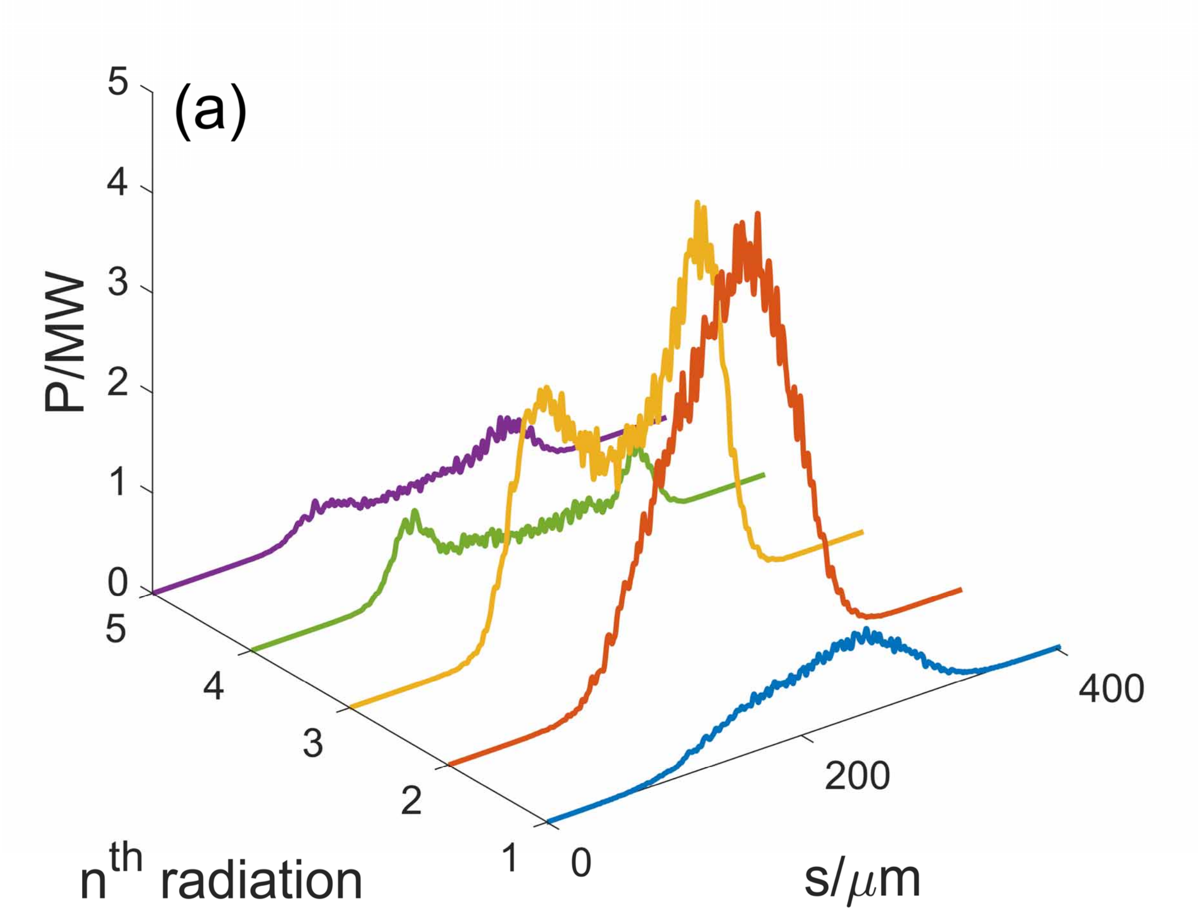
The twiss functions (left), emittance evolution (middle) and vertical beam size evolution (right)



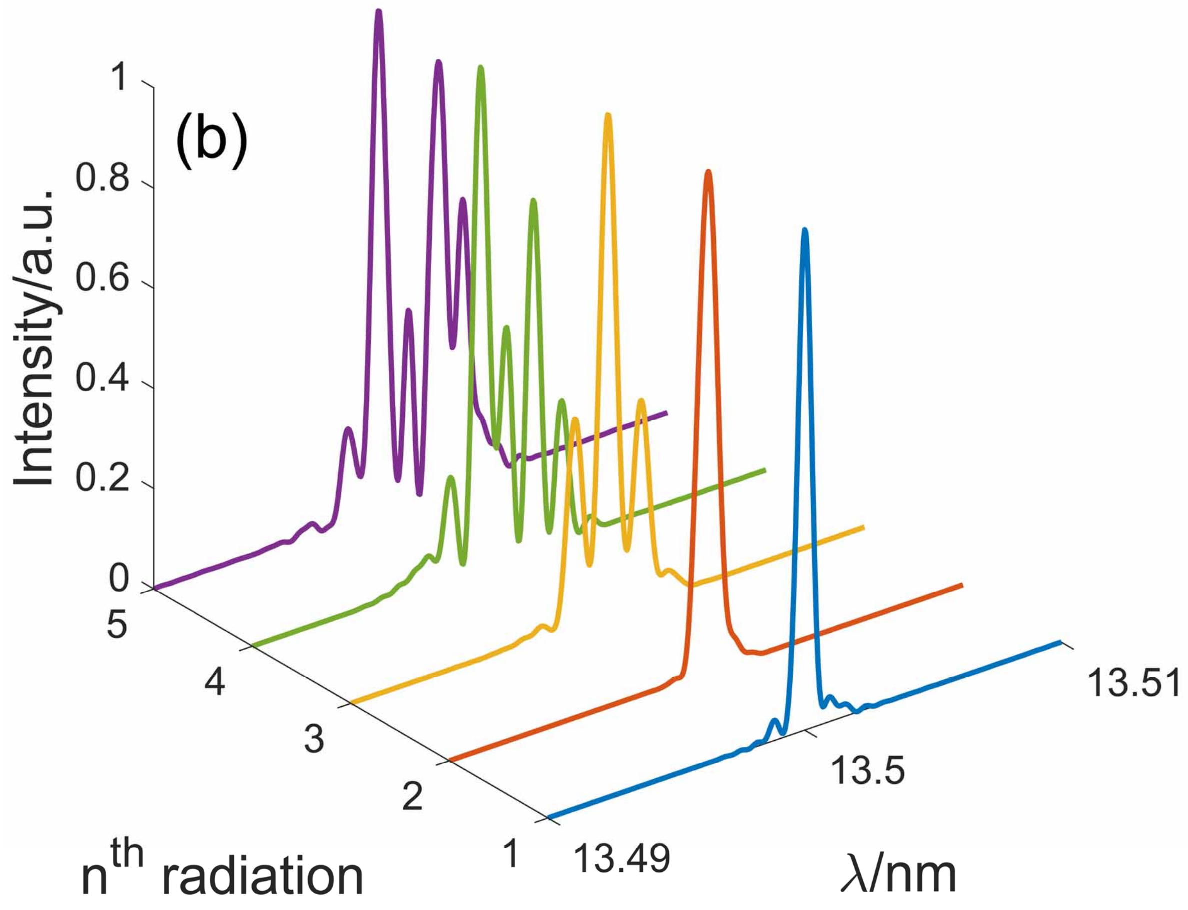
Longitudinal phase space and bunching factor of the beam after four times bending system

Multi-pointing system



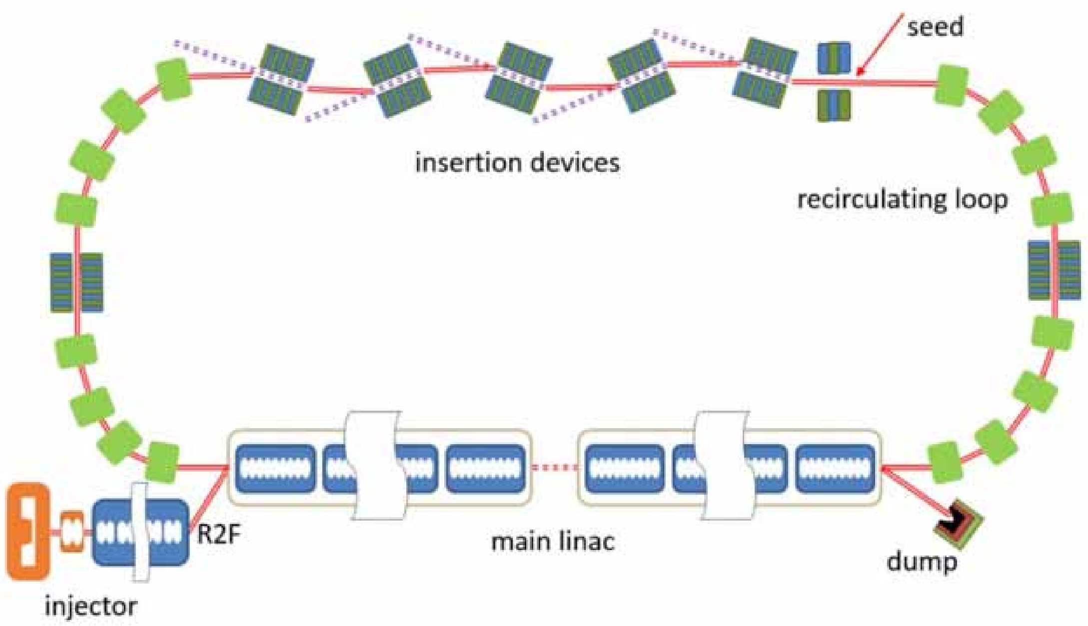


Power distribution



Spectra

3GeV single turn ERL light source

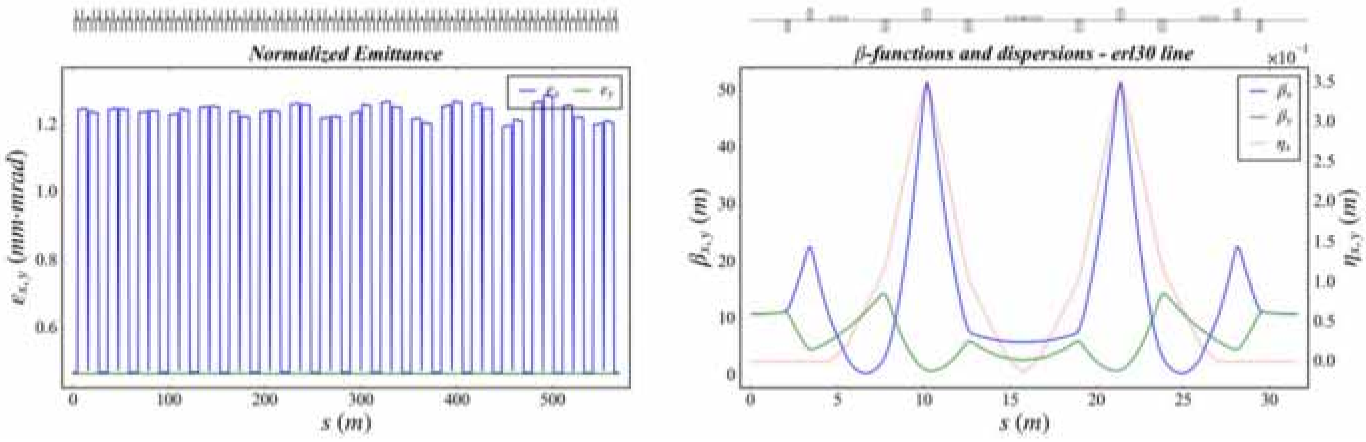


Schematic layout of a 3 GeV single turn ERL light source

Parameters	Value	Units
Beam energy	3	GeV
Normalized emittance	0.5	mm-mrad
Peak current	15	A
Bunch charge	77/8	pC
Repetition rage	1.3	GHz
Average current	100/10	mA

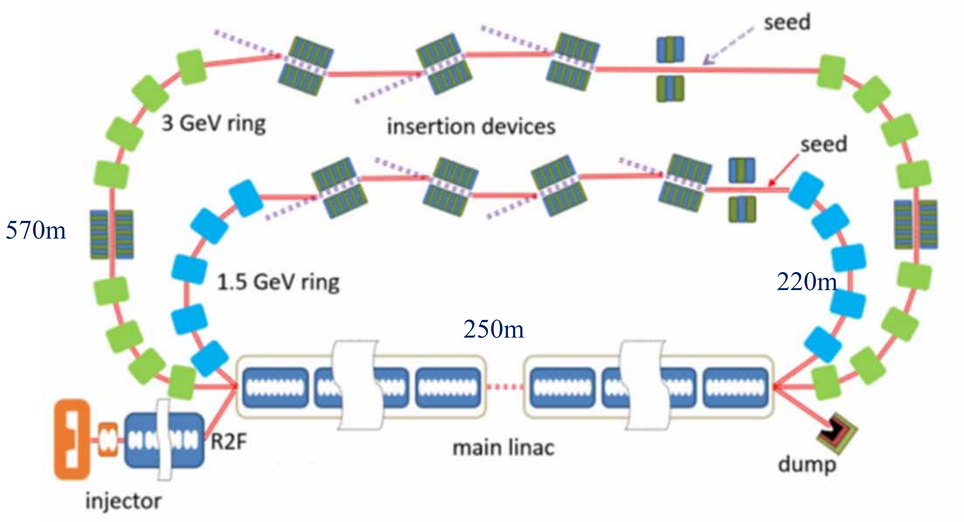
Main beam parameters of the 3 GeV single turn ERL light source

- The recirculating loop has a long straight section (about 500 m) and two 180˚ arcs (570 m long per arc).
- Each arc comprises 18 periodical TBA cells which are isochronous.



The emittance evolution (left) and the optical function in each TBA cell (right)

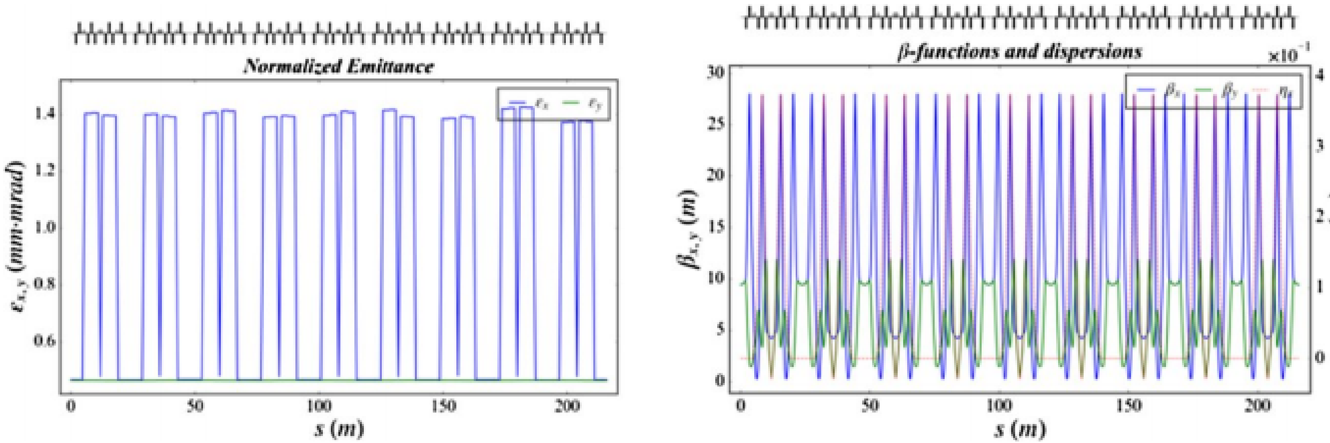
3GeV multi-turn ERL light source



A possible layout for a fully coherent x-ray light source based on ERL

- Multi-turn acceleration and deceleration can reduce the scale of the high energy ERLs significantly
- Half of the electron bunches are seeded in the 1.5 GeV ring and generate EUV coherent radiation
- Another half of the electron bunches are accelerated twice to 3GeV for X-ray radiation generation

- main issue: the maintenance of the beam quality as the electron beam passes through the 1.5 GeV ring
- 3D simulation results show that the quality of the electron beam can be well maintained to generate high repetition rate coherent x-ray pulses



The emittance evolution (left) and the optical function in each TBA cell (right)

Summary

- We report a new method for high repetition rate fully coherent pulse generation by taking fully advantages of the ERL and ADM.
- The proposed light source holds the merits such as fully coherent radiation with a brightness 5–6 orders of magnitude higher than that of a DLSR with the same beam energy, and much higher repetition rate comparing with an FEL.
- We also propose two future ERL light sources to generate fully coherent EUV and X-ray radiation, and consider a multi-point radiation emitting system consists of DBAs and radiators to support multi-user operation.
- However, limited by the photoinjector and the HOM BBU effect, the 100-mA-level average current is a big challenge. Meanwhile, dominated by the injector, the energy jitter, temporal jitter and the temporal stability might become larger than storage rings.
- The ADM technique has not been experimentally demonstrated yet, but a proof-of-principle experiment of ADM is under preparation at the Shanghai Soft X-ray FEL facility.

Thank you!