ERL Based Fully Coherent Light Source

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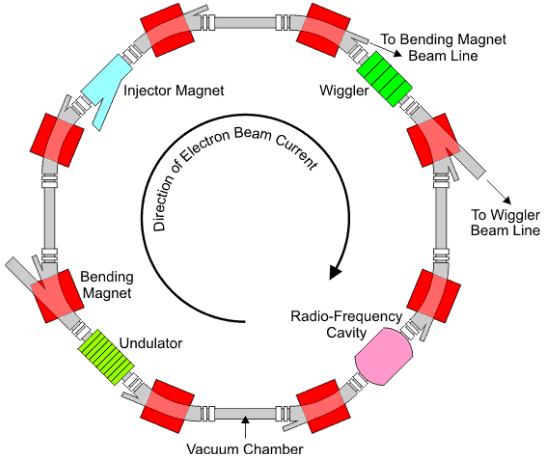
Outline

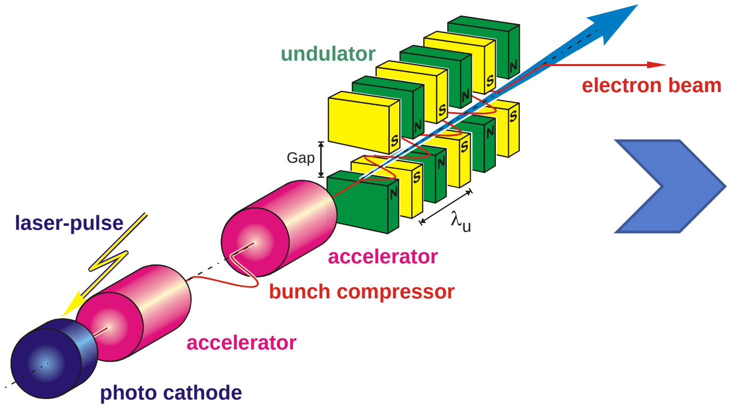
- From Synchrotron Radiation to Coherent Radiation
  - Synchrotron radiation and coherent radiation
  - ADM Scheme in storage ring and ERL
  - Round to flat beam technique
- An ERL Light Source for Fully Coherent Radiation
  - Concept design: high-flux mode and high-resolution mode
  - Multi-radiation source consideration
- Considerations on ADM based ERL Light Sources
  - 3GeV single turn ERL&1.5GeV double-turn ERL light sources
- Summary

Light Sources for Synchrotron Radiation and Coherent Radiation

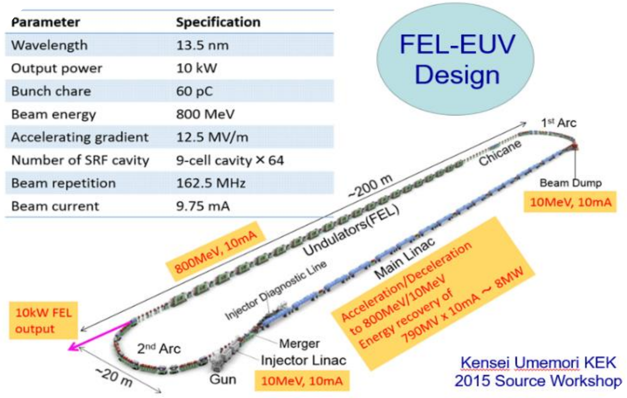
technological maturity



Storage ring (SR)



Free electron laser (FEL)



Energy recovery linac (ERL)

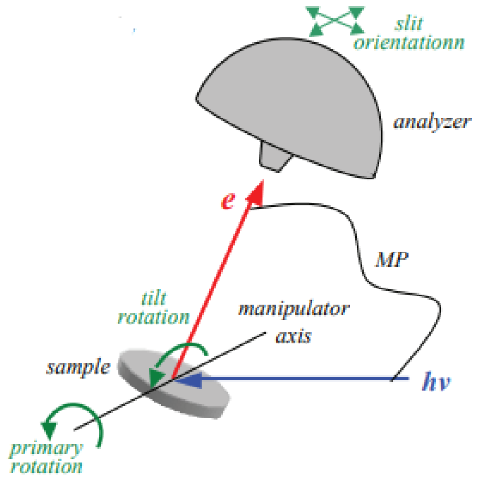
	High repetition rate	High peak Power	High average power	Coherence	technological maturity	Multi-beam line
DLSR*	☆☆☆	☆	☆		☆☆☆	☆☆☆
FEL	☆☆	☆☆☆	☆	☆☆☆	☆☆	☆
ERL	☆☆☆	☆☆	☆☆☆	☆☆☆	☆	☆☆

*Diffraction Limited Storage Ring

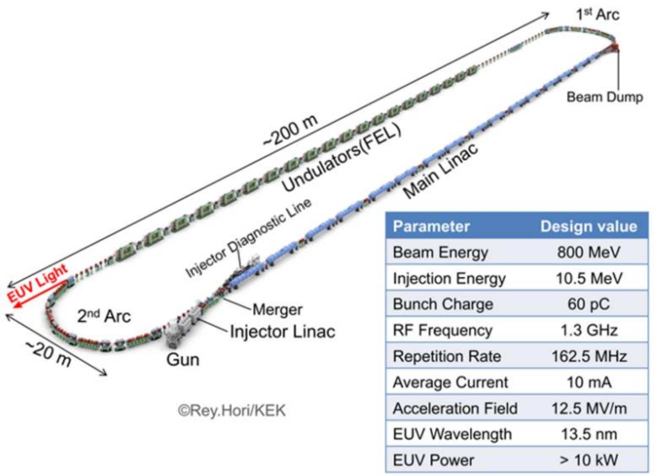
The current challenge for ERL is its relative low peak current that is hard to support high FEL gain in short wavelength

ERL Based Short Wavelength Coherent Radiation

- Able to generate high-repetition rate coherent light pulse, which is necessary for EUV/SX-ARPES.
- A possible candidate of a high-power EUV light source for lithography.
- Highly coherent in both transverse and longitudinal, compared with the DLSR only in transverse.



SX-ARPES endstation:experimental geometry featuring grazing X-ray incidence and vertical measurement plane



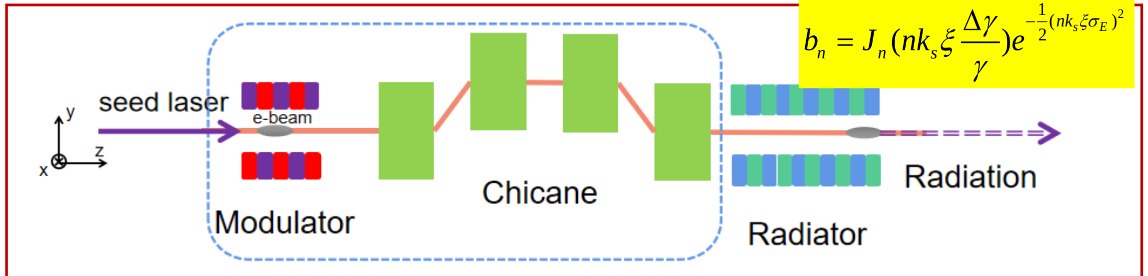
Parameter	Design value
Beam Energy	800 MeV
Injection Energy	10.5 MeV
Bunch Charge	60 pC
RF Frequency	1.3 GHz
Repetition Rate	162.5 MHz
Average Current	10 mA
Acceleration Field	12.5 MV/m
EUV Wavelength	13.5 nm
EUV Power	> 10 kW

Design and specification of the ERL-FEL light source for EUV lithography.

Strocov V N, Kobayashi M, Wang X, et al. Soft-X-ray ARPES at the Swiss Light Source: From 3D materials to buried interfaces and impurities[J].

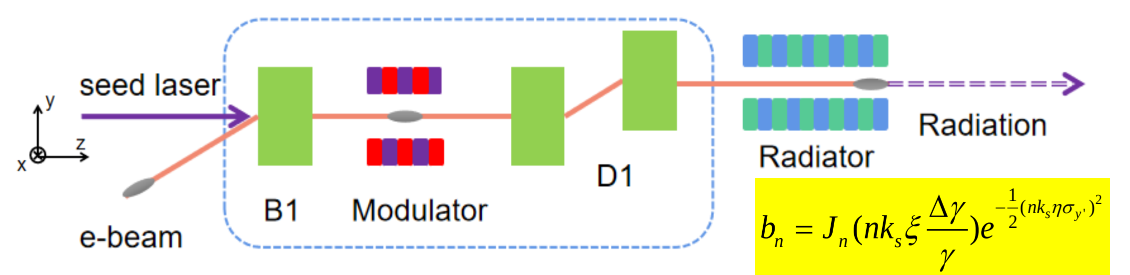
Nakamura N, Kawata H, Kako E, et al. Challenges towards industrialization of the ERL-FEL light source for EUV lithography[c].

Coherent Radiation Schemes: CHG vs ADM



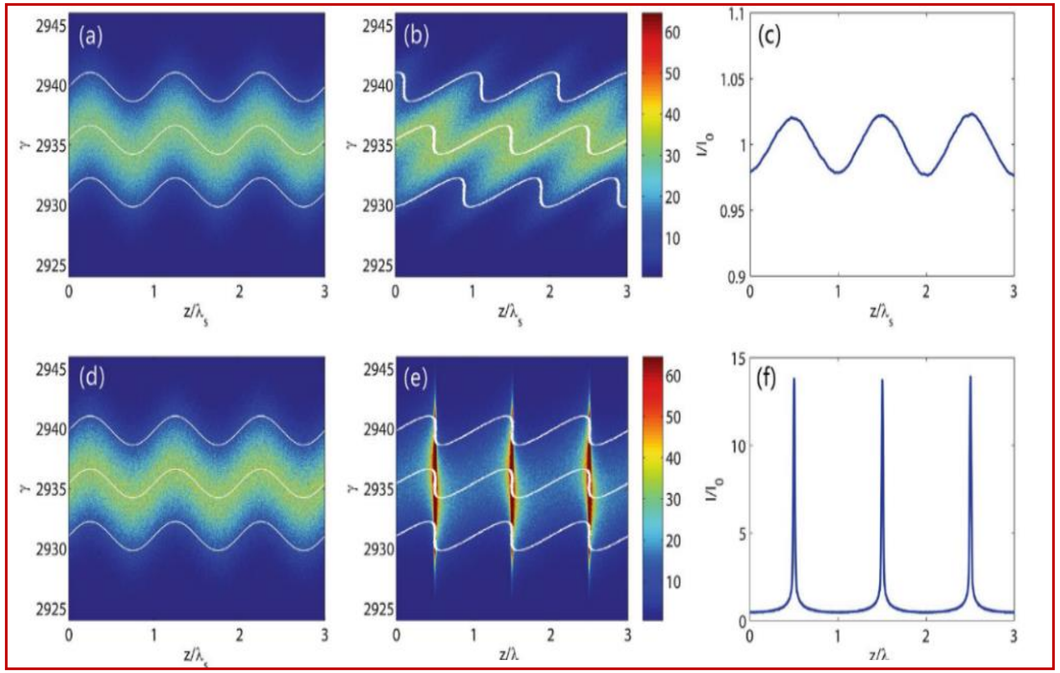
$$b_n = J_n(nk_s\xi\frac{\Delta\gamma}{\gamma})e^{-\frac{1}{2}(nk_s\xi\sigma_E)^2}$$

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)



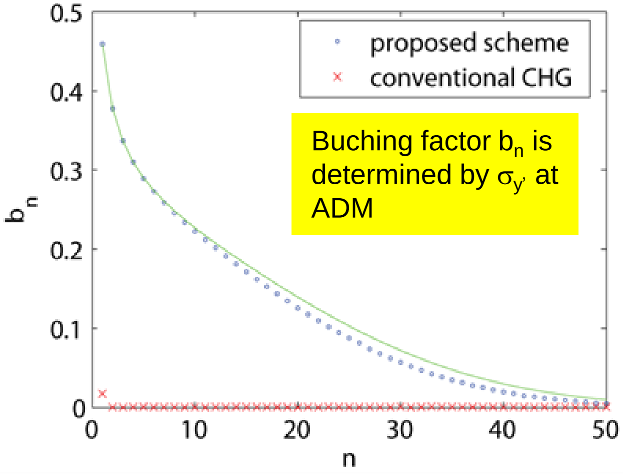
For the normal CHG, the width of the current spike:

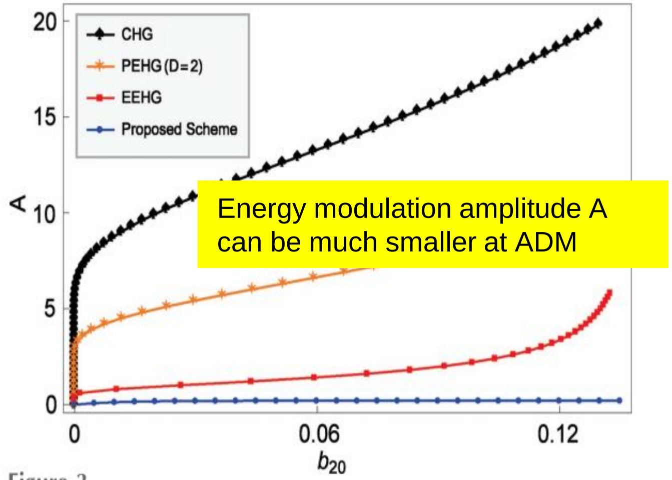
$$\Delta z = \xi\sigma_E$$

For the ADM:

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

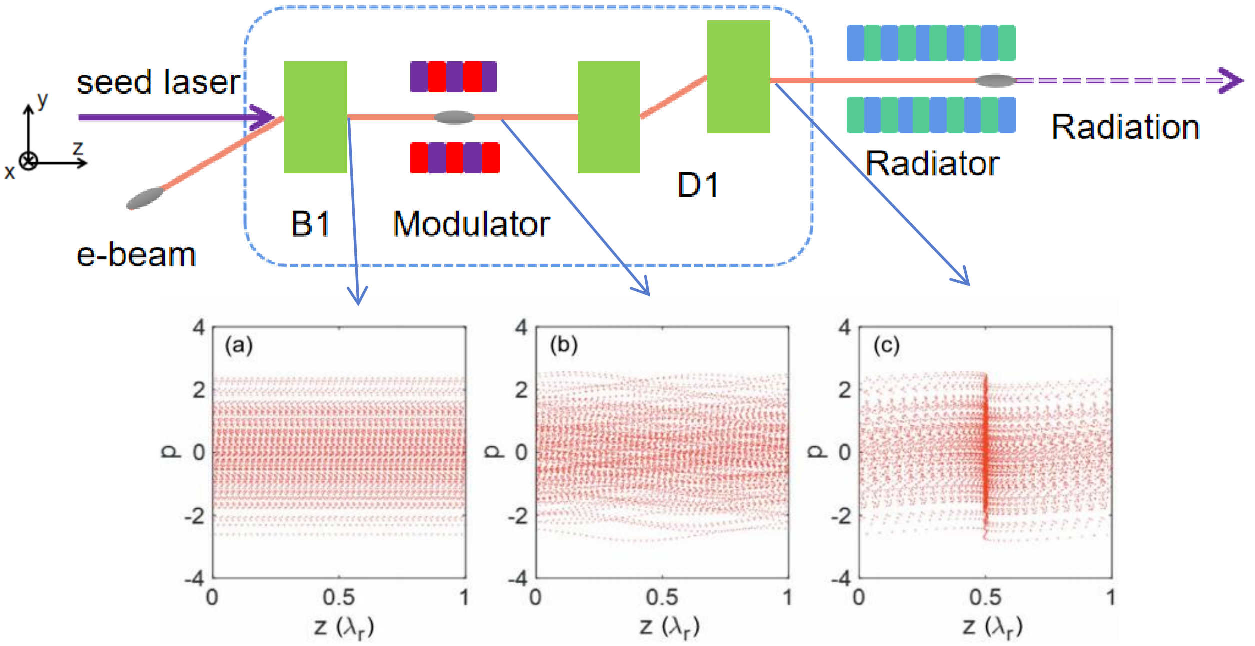
ξ: momentum compaction, σ_E: bunch energy spread





Chao Feng, Zhentang Zhao, Scientific reports, 7, (2017): 4724
Xiaofan Wang, et al. Journal of synchrotron radiation 26 (2019): 677-684

ADM Scheme: Angular-Dispersion induced Microbunching



Angular-dispersion induced microbunching

- Consists of a seed laser, a bend (B), a modulator (M), and a dispersion (D).
- The required laser power for ADM is about 3 orders of magnitude lower than that required for normal harmonic generation techniques.
- The bunching factor is determined by the initial spread of y', $\sigma_{y'}$, thus the R2F will be used in ERL to decrease vertical emittance for larger b_n.

$$\boldsymbol{R} = \boldsymbol{R}_D \cdot \boldsymbol{R}_M \cdot \boldsymbol{R}_B = \begin{pmatrix} 1+hb\eta & L & h\eta & \eta-(L-L_b)b \\ 0 & 1 & 0 & -b \\ b(1+h\xi) & \eta & 1+h\xi & \xi-\eta b \\ hb & 0 & h & 1 \end{pmatrix}$$

$$\boldsymbol{R}_B = \begin{pmatrix} 1 & L_B & 0 & 0 \\ 0 & 1 & 0 & -b \\ b & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \boldsymbol{R}_M = \begin{pmatrix} 1 & L_M & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & h & 1 \end{pmatrix} \quad \boldsymbol{R}_D = \begin{pmatrix} 1 & L_D & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

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

Chao Feng, Zhentang Zhao, Scientific reports, 7, (2017): 4724
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Round to Flat Beam 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.

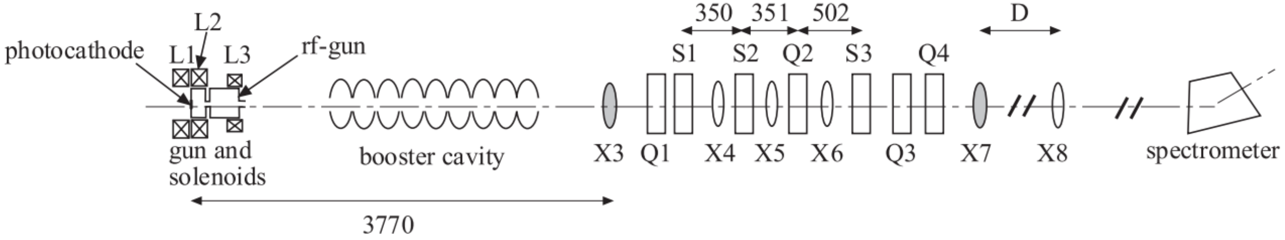
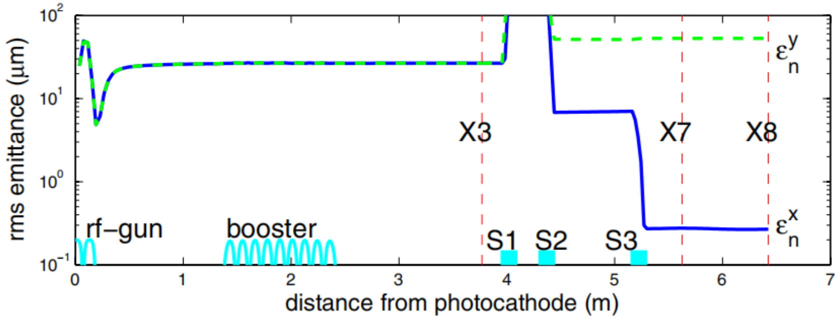


FIG. 1. Overview of the Fermilab/NICADD photoinjector. "X" refer to diagnostics stations (beam viewers, and/or slit location), "L" to the solenoidal lenses, "Q" to quadrupoles, and "S" to the skew quadrupoles. All distances are in mm, with $D = 800$ (or 1850 for the data presented in Fig. 7).

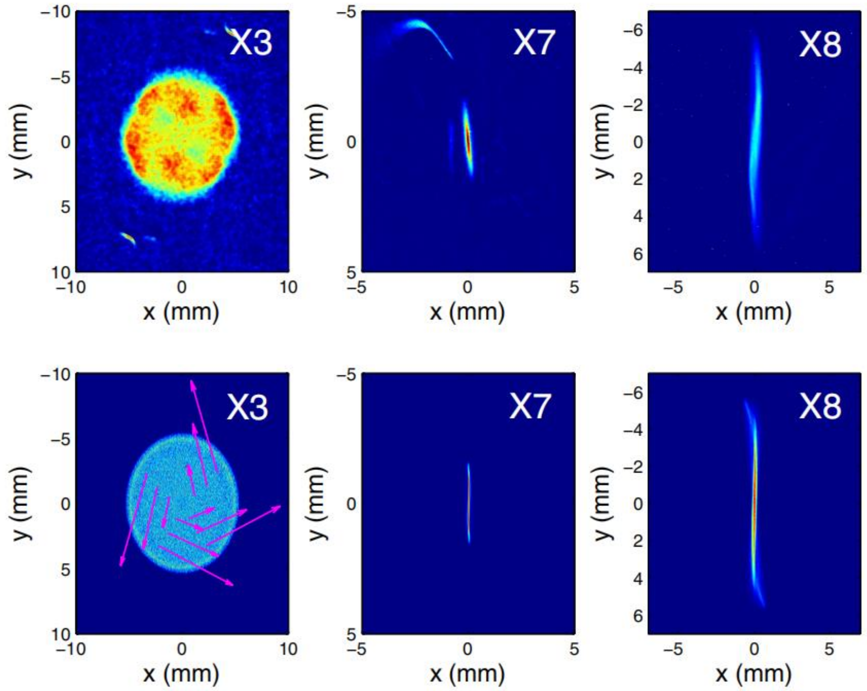
$$\varepsilon_n^{\pm} = \sqrt{(\varepsilon_n^u)^2 + (\beta\gamma\mathcal{L})^2}$$

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

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



Evolution of beam normalized emittances along the beam line

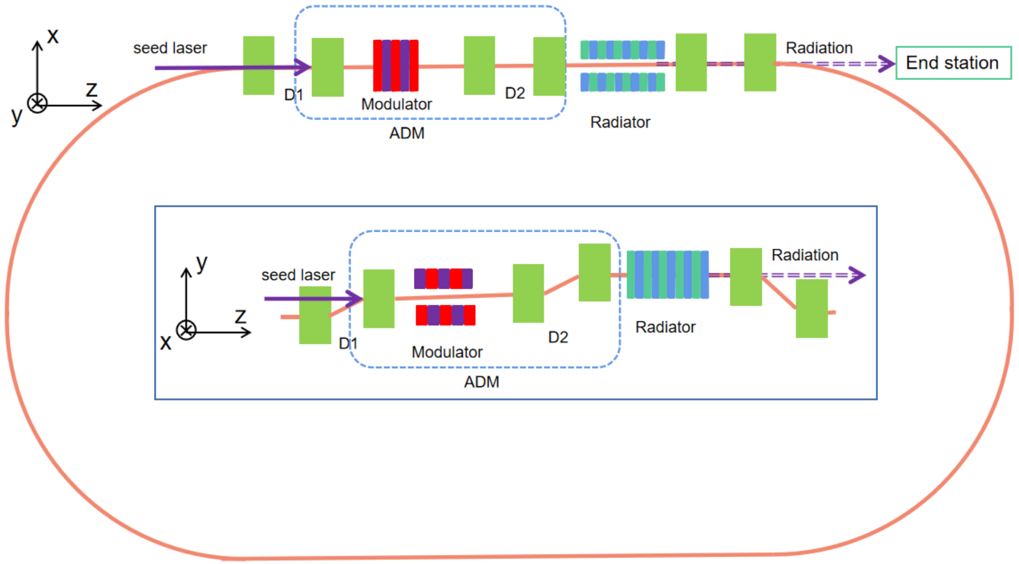


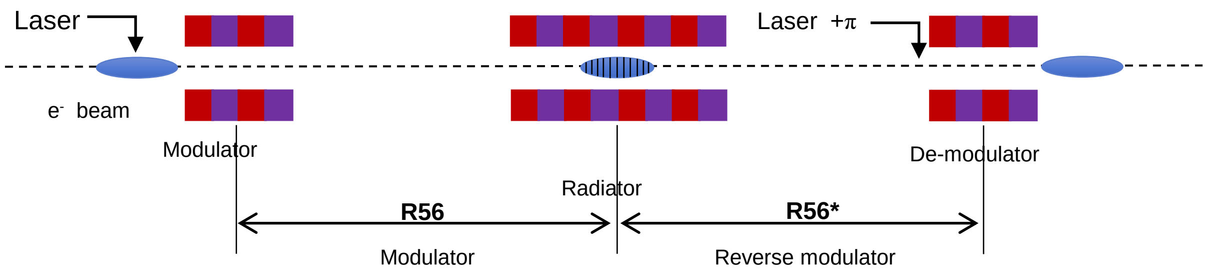
Example of the transformation of the incoming angular-momentum-dominated round beam into a flat beam.
Top row: measurements; bottom row: corresponding numerical simulations.

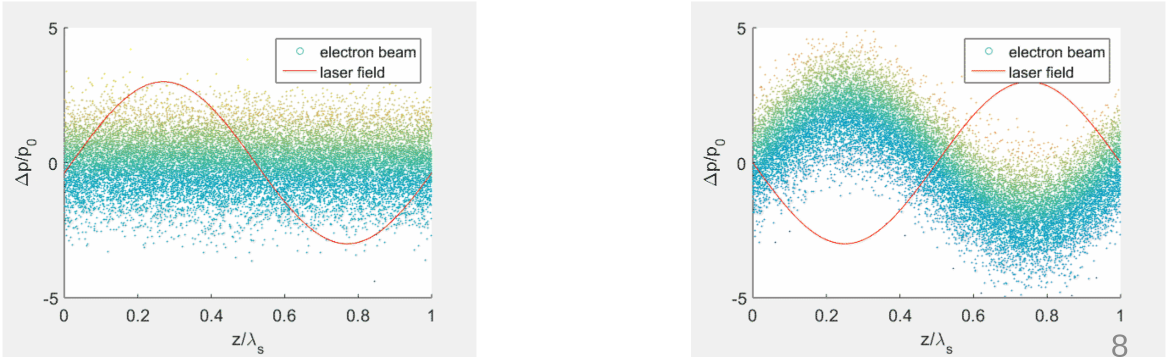
Piot, P., Sun, Y.-E. & Kim, K.-J. Photoinjector generation of a fat electron beam with transverse emittance ratio of 100. Phys. Rev. ST Accel. Beams 9, 031001. https://doi.org/10.1103/PhysRevSTAB.9.031001 (2006).

Introducing ADM Scheme into Storage Ring

- ADM was proposed initially to manipulate the electron beam in storage rings. There are some limitations:
  - The repetition rate is still limited by the damping time of the storage ring.
  - A complicated scheme called "modulation-antimodulation" beam manipulation technique has to be adopted.
- By inserting a reversal stage, the beam can return to its initial state and can be reused on its next turn to achieve high rep-rate and much higher average power.
- Typically requires very tight tolerances to perform the reverse modulation.

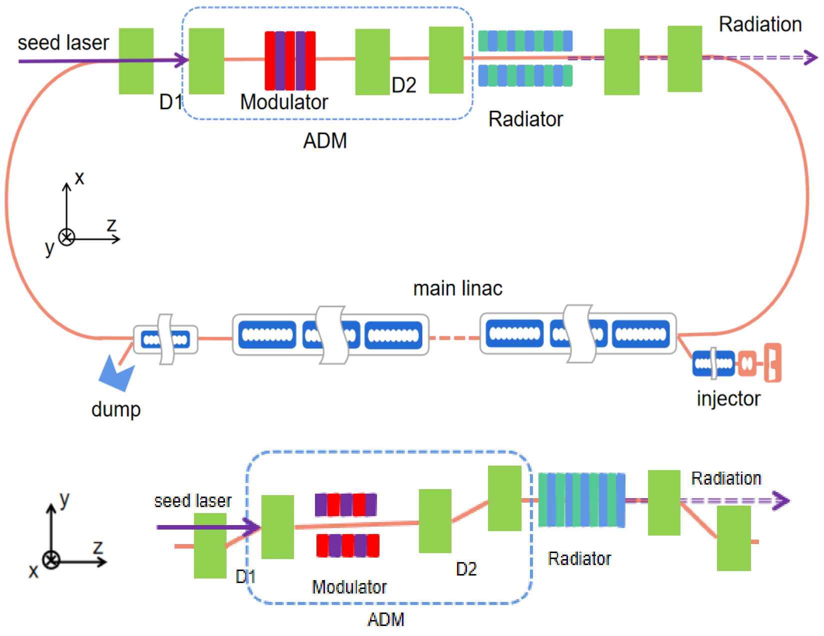






ERL has none of these limitations!

Introducing ADM into ERL to Enhance Its Radiation Power

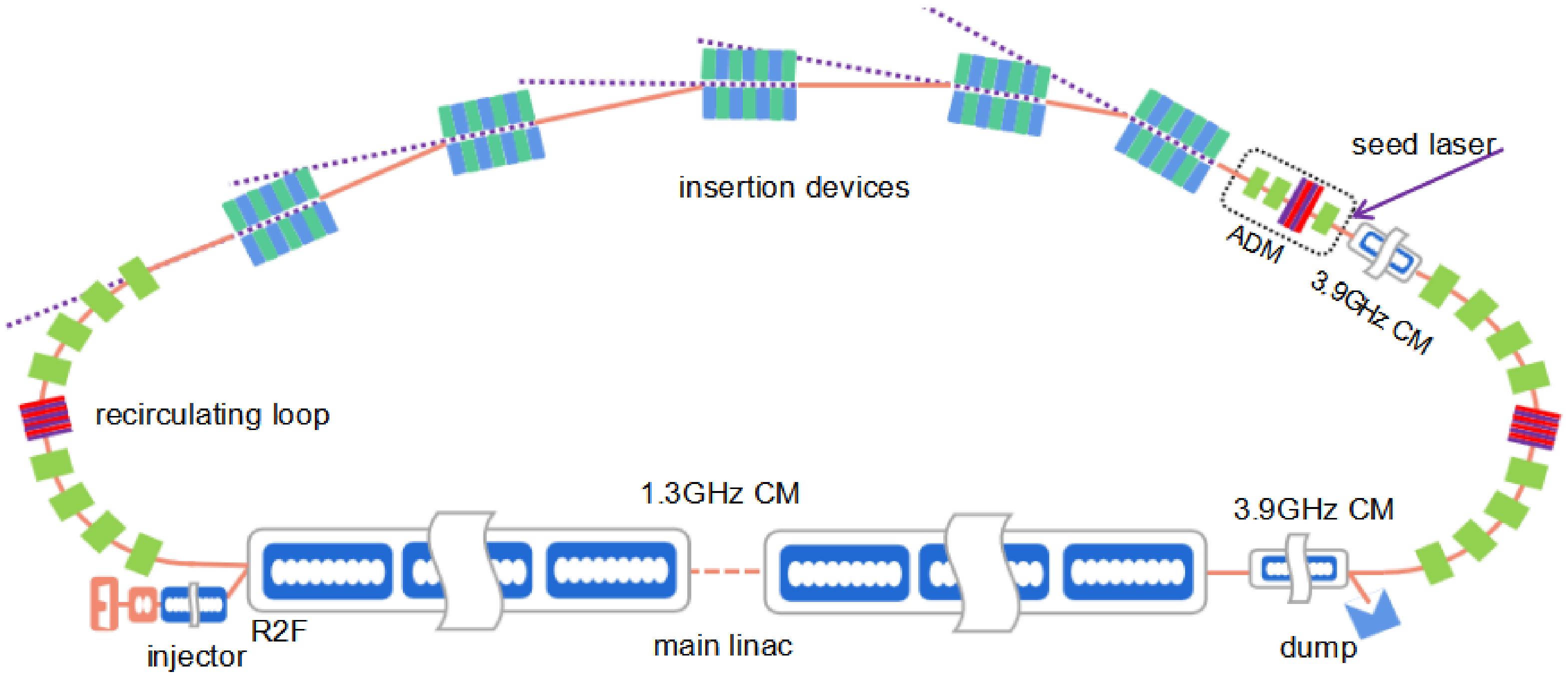


Zhao Z T, Wang Z, Feng C, et al. Scientific Reports, 2021, 11(1): 1-9.

- 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 $10^{4\sim5}$ times higher than that of DLSR with the same beam energy**
- **The average power can be over 100W at 13.5 nm**

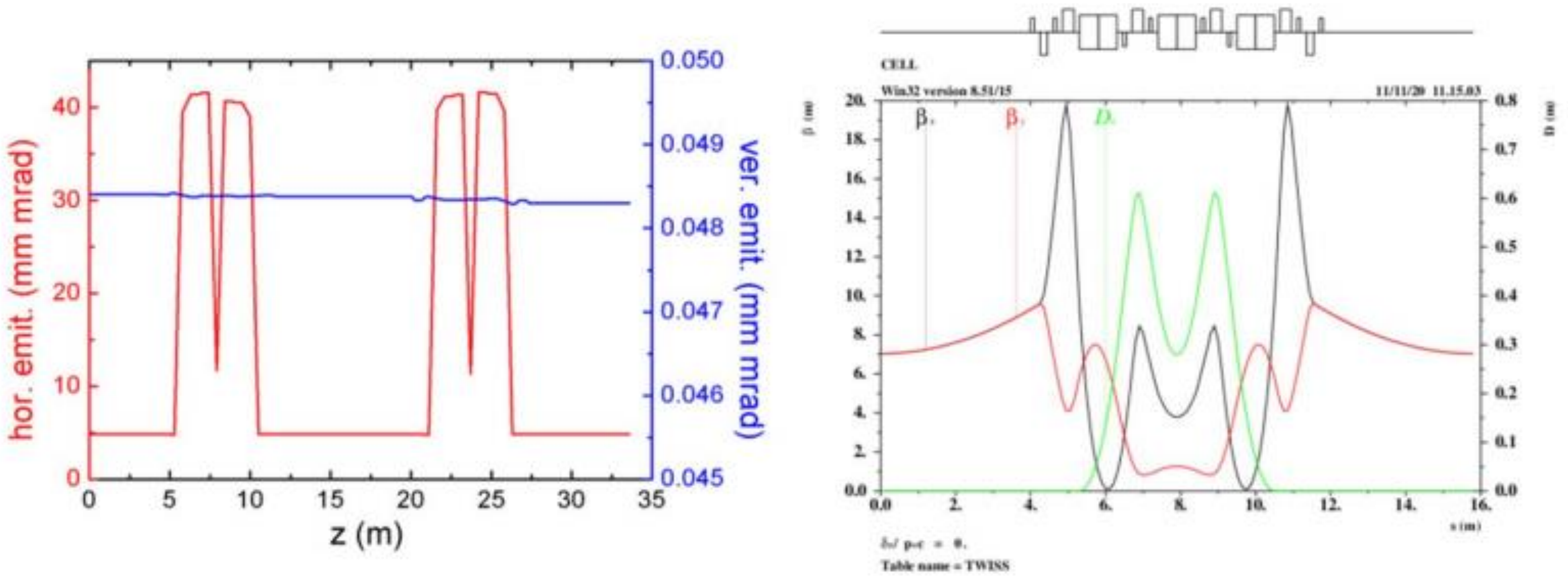
Concept Design: The layout of the EUV Based Fully Coherent Light Source



- R2F: vertical emittance be reduced to 0.05 mm-mrad and horizontal emittance be increased to about 5 mm-mrad
- main linac: 90 m, boost the electron beam to about 600 MeV
- 3.9 GHz cavities in rear part of the linac: compensate the nonlinear energy spread
- 3.9 GHz cavities in rear part of the recirculating loop: compensate the project energy chirp (achieved in the main linac)

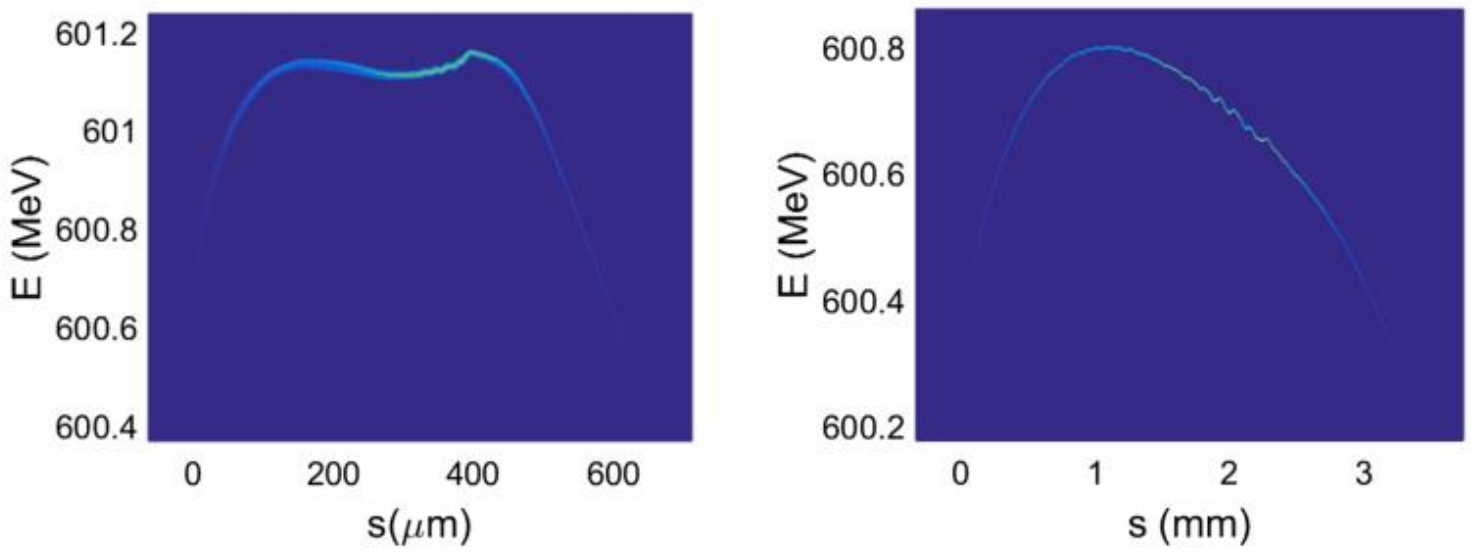
Zhao Z T, Wang Z, Feng C, et al. Scientific Reports, 2021, 11(1): 1-9.

Concept Design: Lattice for the Arc



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

Concept Design: High-flux Mode and High-resolution Mode



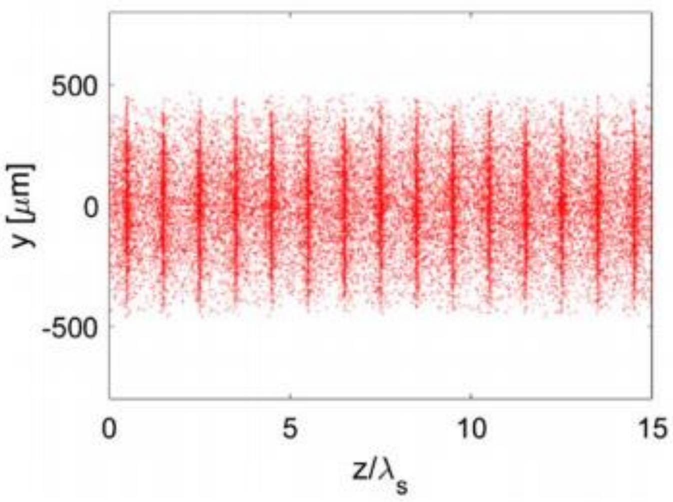
Longitudinal phase space of the electron beam in high-flux mode (left) and high-resolution mode (right) at the entrance of undulator

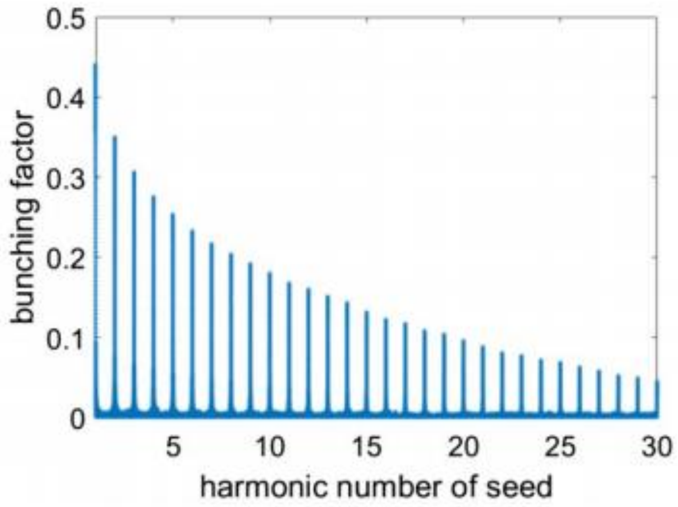
- **High-flux mode**:
  relatively high current (~100A), compress to about 700 fs, unspoiled electron beam quality after the arc.

- **High-resolution mode**:
  relatively long electron bunch, peak current maintains ~15 A without compression

Concept Design: High-flux Mode and High-resolution Mode

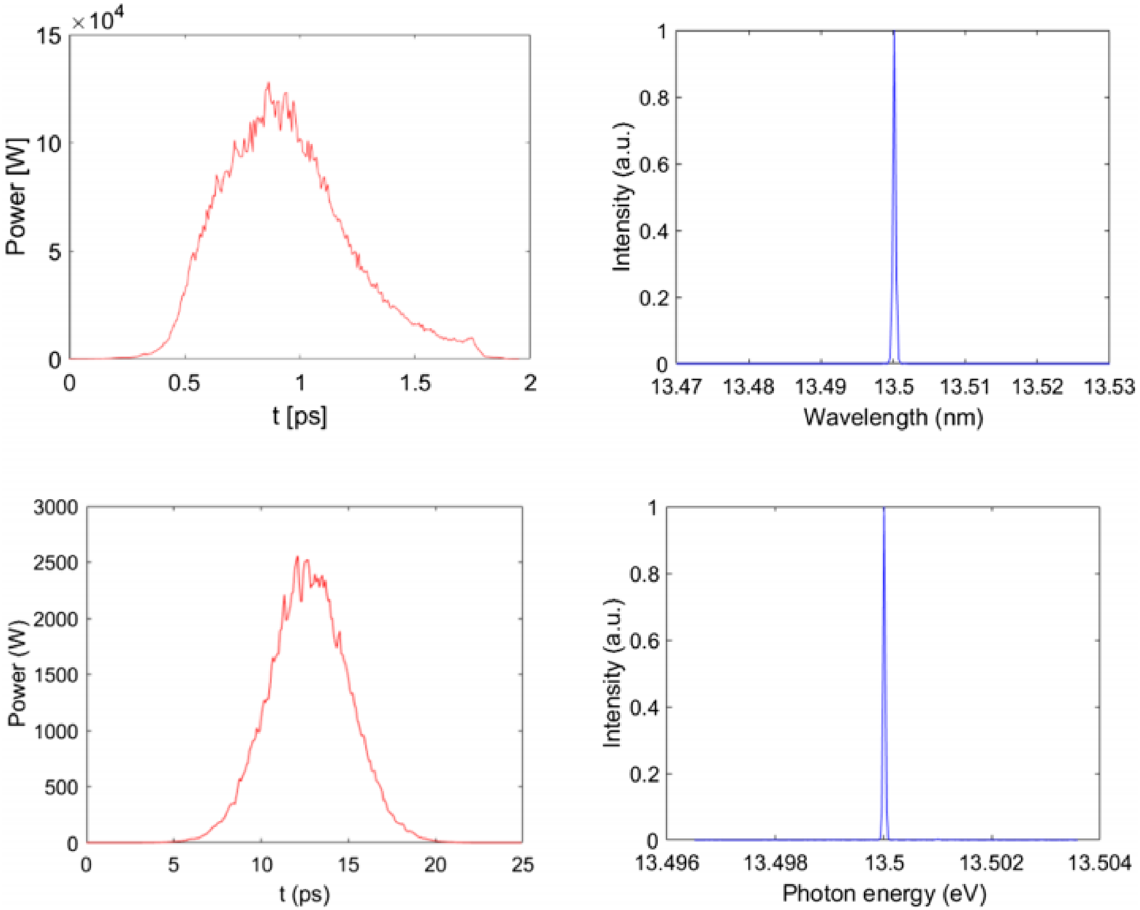
Parameters	Values (high flux/resolution)
Bending angle	0.2 rad
Modulator period	3.5 cm
Modulator length	3 m
Radiator period	2 cm
Radiator length	3 m
Seed laser wavelength	256.5 nm
Seed laser duration	2/10 ps
Seed laser peak power	10 kW
Radiation wavelength	13.5 nm
Radiation peak power	120/2.5 kW
Radiation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





Simulation results of the density modulation and bunching factors at various harmonics of the seed laser (~257nm seed laser from forth harmonic generation of the fiber laser).

Concept Design: High-flux Mode and High-resolution Mode



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

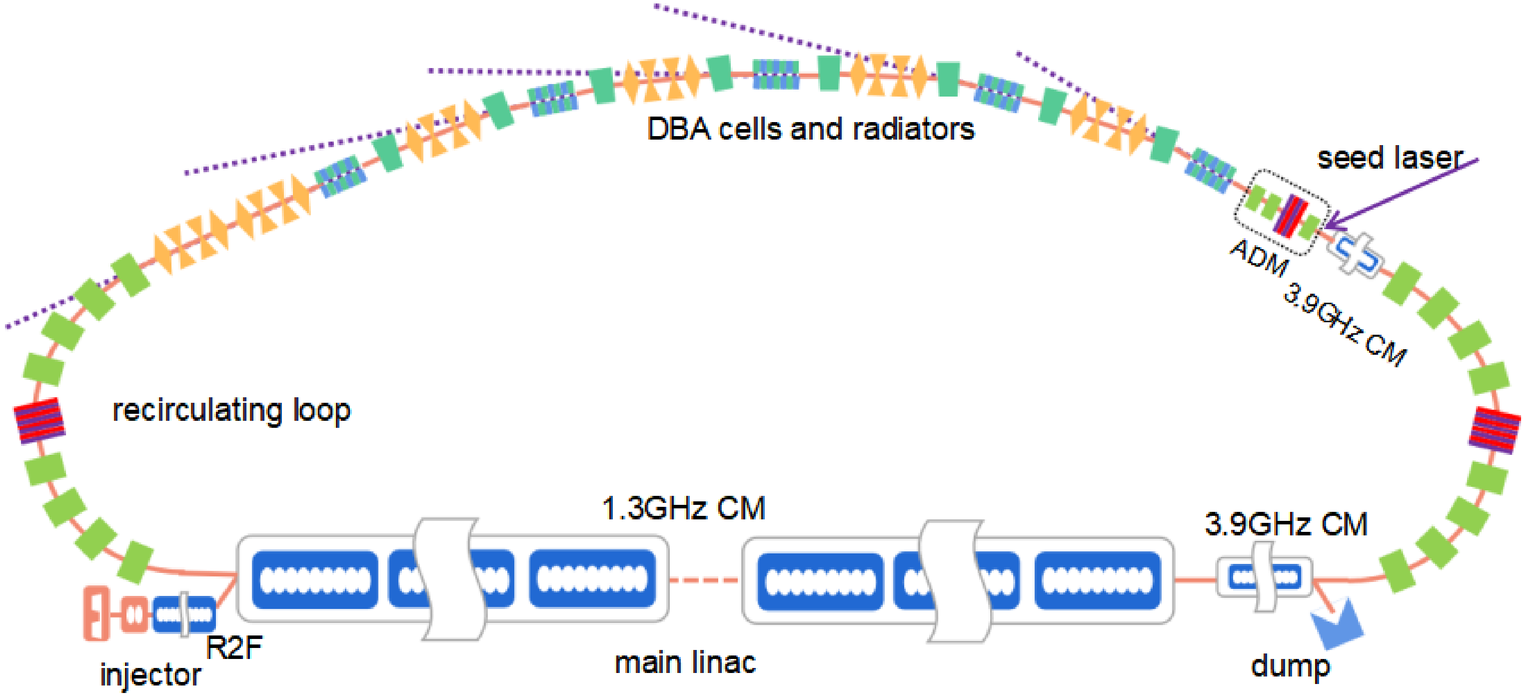
- high-flux mode:
  peak power: 120kW
  spectral bandwidth: 3.5meV
  average output power: 100W
  average brightness: 10^{25} phs/s/mm^2/mrad^2/0.1%BW

- high-resolution mode (suitable for ARPES):
  radiation pulses length: 6ps
  spectral bandwidth: 0.4meV@13.5 nm

Parameters	Value	units
Beam energy (injector)	15	MeV
Beam energy (linac)	600	MeV
Normalized emittance (injector)	0.5	mm-mrad
Normalized emittance (linac/undulator)	5/0.05	mm-mrad
Bunch charge	77	pC
Pulse duration (linac, FWHM)	4	ps
Pulse duration (undulator, FWHM)	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 (r)	0.5	mm
Bend angle in the ring	30	°

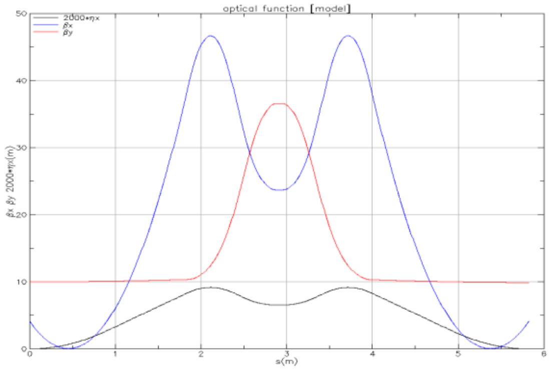
Beam parameters in the injector, linac and recirculating loop

Multi-radiation Source Consideration



parameters	value	units
bend length	0.9	m
bend angle	3	mrad
Q1 length	0.54	m
Q1 strength	2.5	1/m^2
Q2 length	0.38	m
Q2 strength	-2.29	1/m^2
S1 length	0.3352	m
S1 strength	32.75	1/m^3
S2 length	0.24	m
S2 strength	33.32	1/m^3

main parameters of the DBA

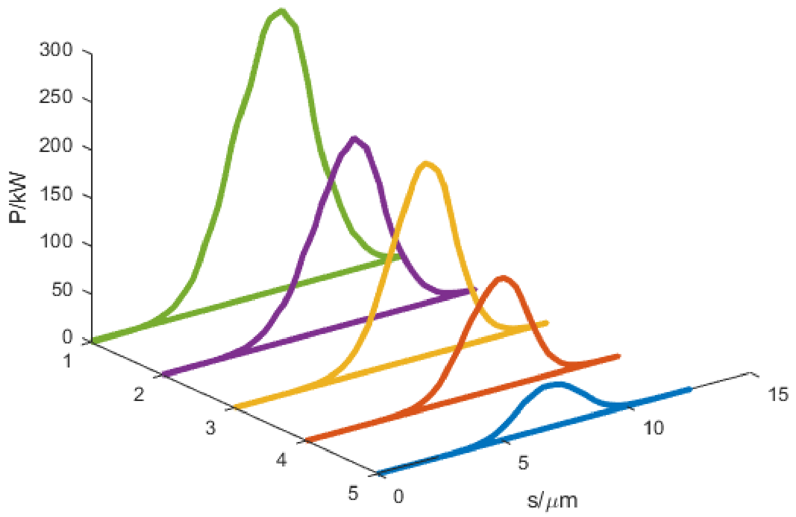


The optical function of one DBA cell

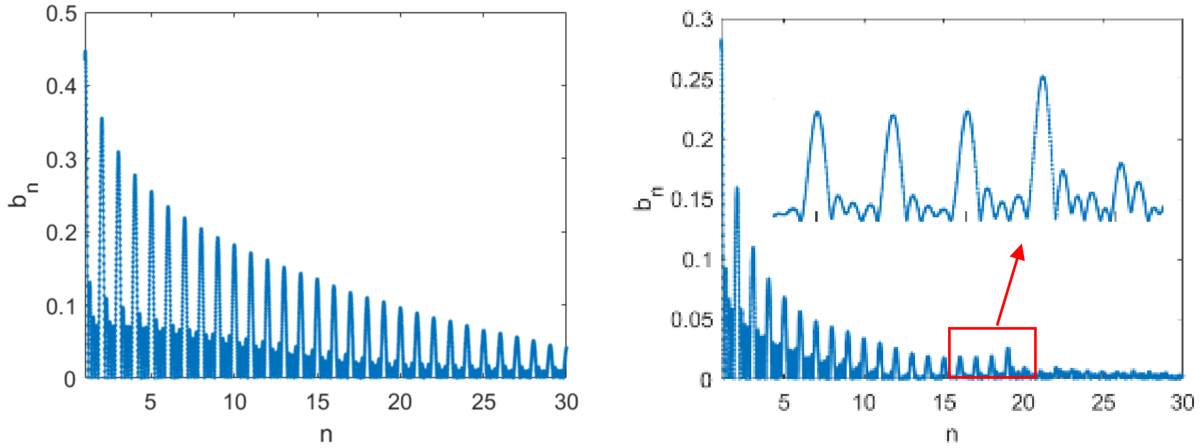
- To preserve the phase space, the parameters of bend are set to make the R_{56} of the DBA counteract that of the upstream radiator.
- To eliminate transverse dispersion, we optimize the strengths and locations of the quadrupoles and sextupoles.

Multi-radiation Source Consideration

- After the fourth bending cell, the bunching factor at n=19 (13.5nm) decreases from 10% to 2.5%, mainly caused by the second order terms of transfer matrix $T_{5ij}(i,j = 1,2,3,4)$. This can be improved by a four DBA cells lattice.
- If ignoring high order terms, the bunching factor of electron beam after the bending cell would increase greatly, indicating that the DBA cell can compensate the $R56$ of the upstream undulator and realize "isochronous" partly.

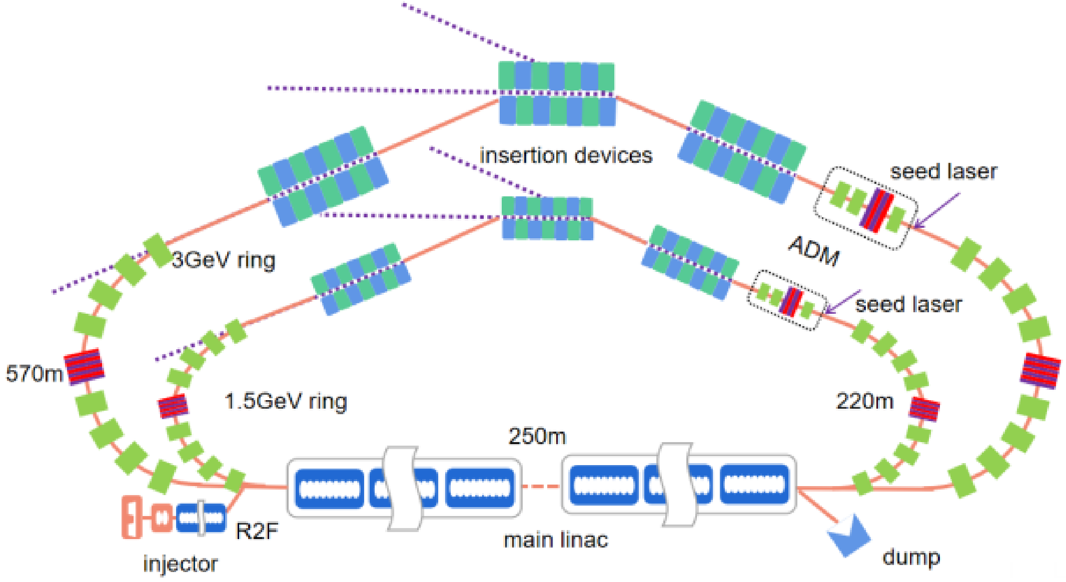


The radiation peak powers at the exit of five radiators (1.5m) respectively.



The bunching factor of the initial electron beam(left)
and the electron beam at the exit of the fourth bending(right).

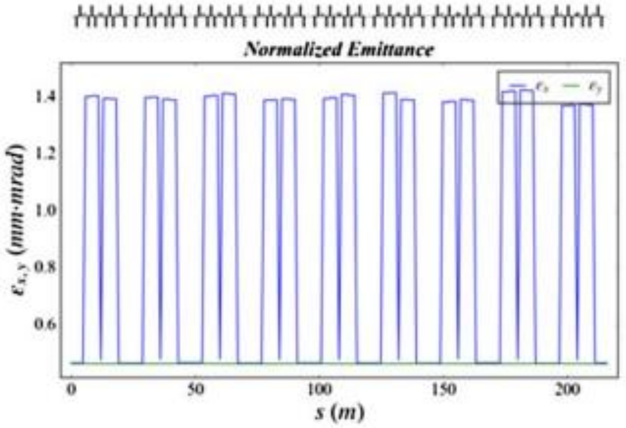
A Possible Design for a 1.5GeV Double-turn ERL Light Source

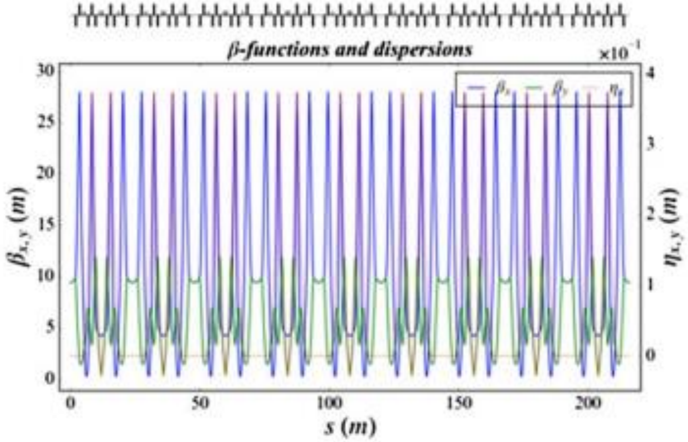


A possible layout for a fully coherent x-ray light source based on ERL

- 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

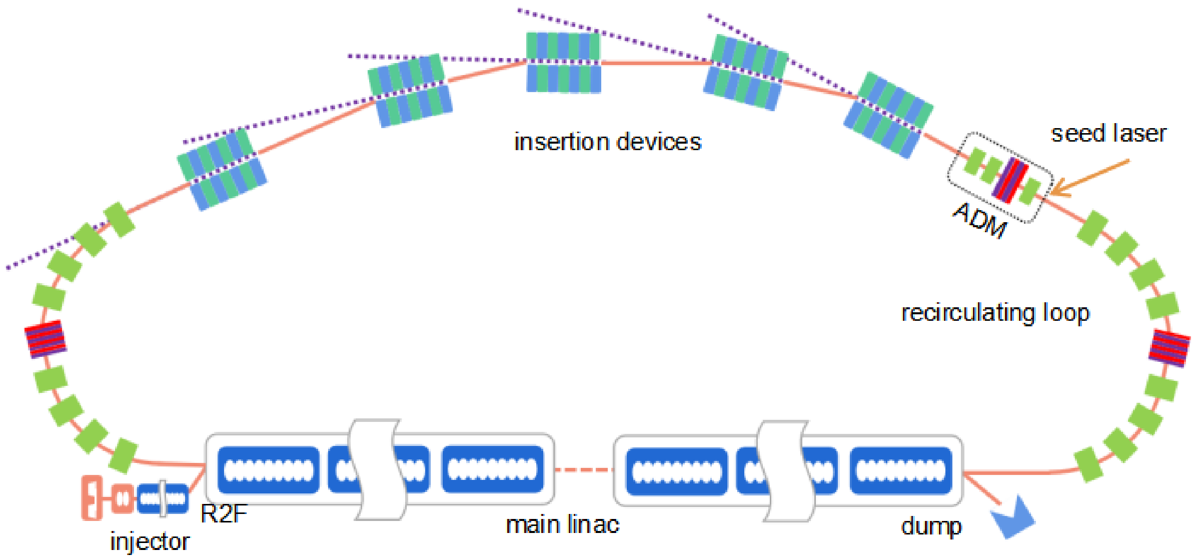
- main issue: the maintenance of the beam quality as the electron beam passes through the 1.5 GeV ring
- 3D simulation results show that the quality of the electron beam can be well maintained to generate high repetition rate coherent x-ray pulses





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

A Possible Design for a 3GeV Single Turn ERL Light Source

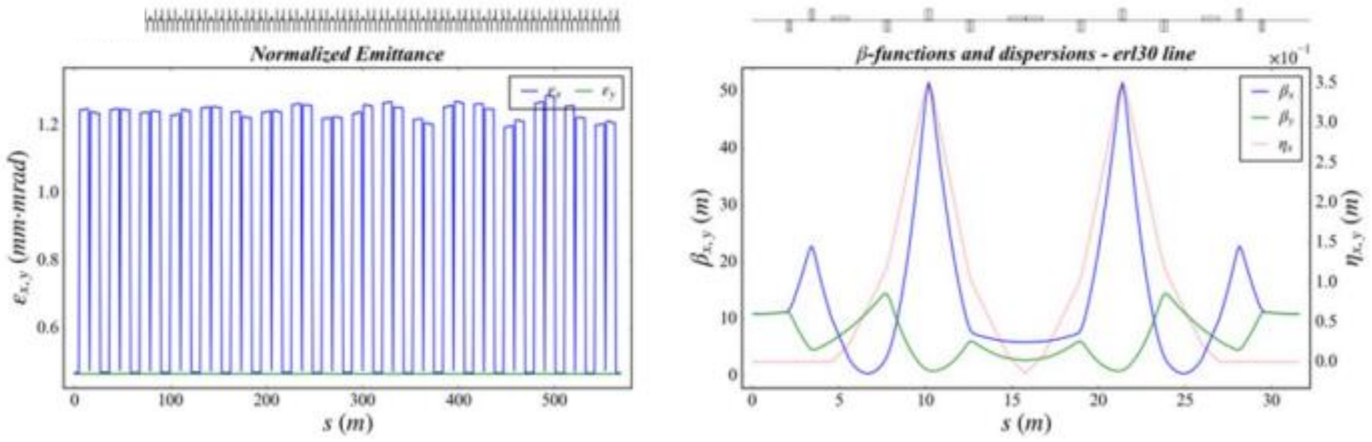


Schematic layout of a 3 GeV single turn ERL light source

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)

Summary

- We report a new method for high repetition rate fully coherent pulse generation by taking 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 proposed two future ERL light sources to generate fully coherent EUV and X-ray radiations, and we considered a multi-radiation source 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 scheme has not been experimentally demonstrated yet, but a proof-of-principle experiment of ADM is under preparation at SARI.

Thank you for your attention!

Acknowledgement

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- Chuanxiang Tang, Xiujie Deng, Renkai Li, Alex Chao from THU, Weishi Wan from ShanghaiTech and Zhenghe Bai from USTC for collaboration and discussions.