Beam dynamics and CSR suppression in an ERL driven X-ray FEL

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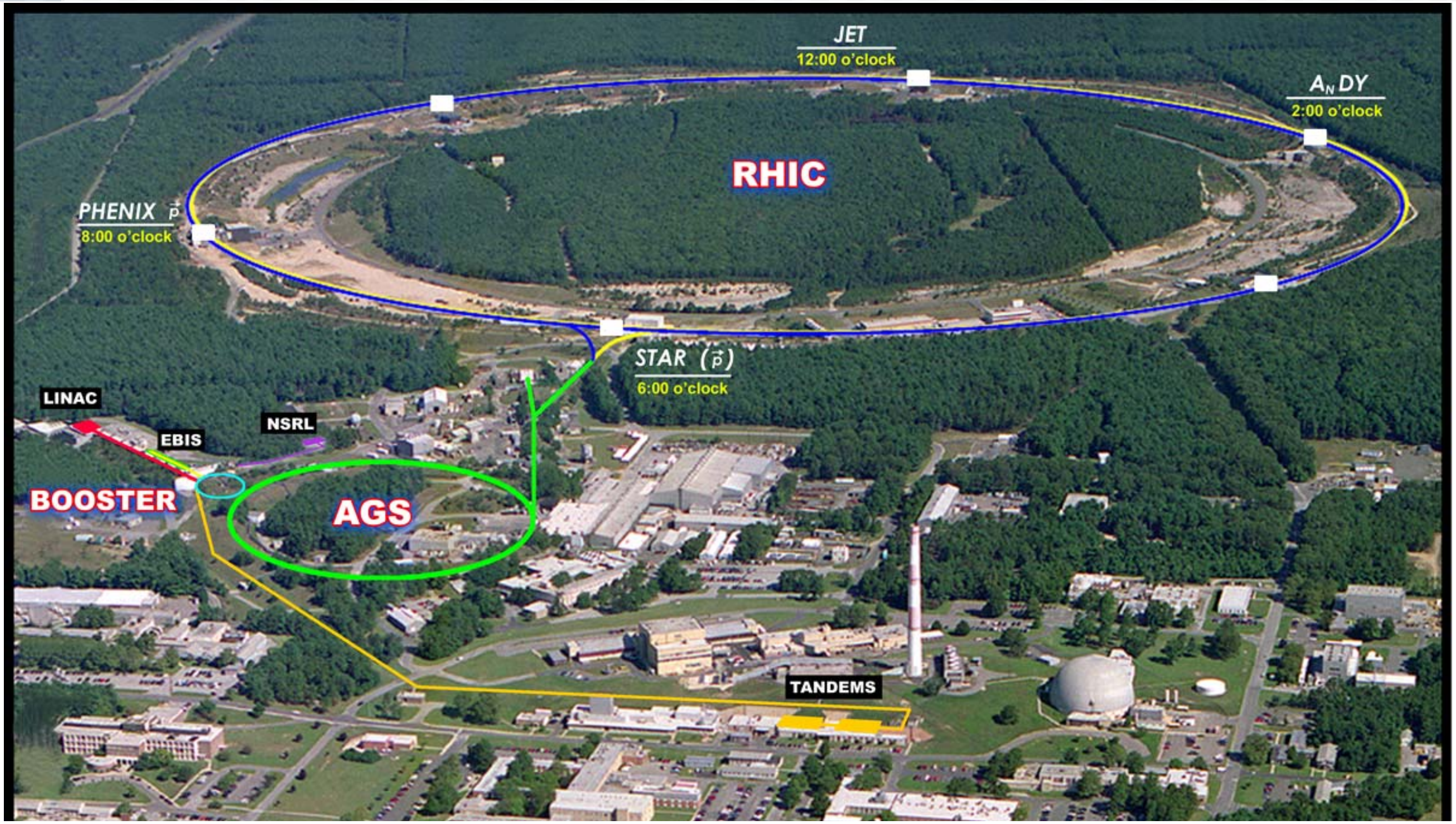
Outline

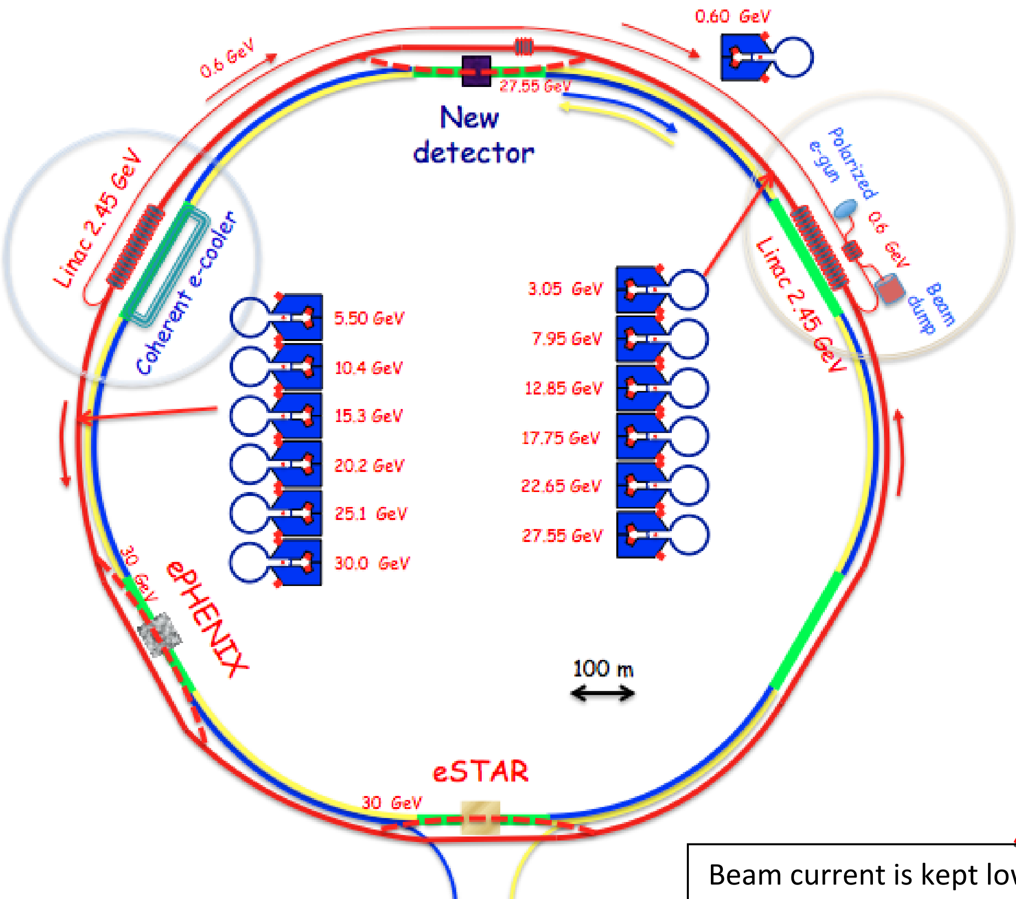
- eRHIC and its options for FEL
- ARCs and their effect on beam properties
- C-shape Bunch compressor and its limitation
- Two stage bunch compressor with minimized CSR effect
- Possible FEL process and its performance
- Summary

eRHIC : an upgrade of RHIC



Add e- accelerator to the existing $2B RHIC

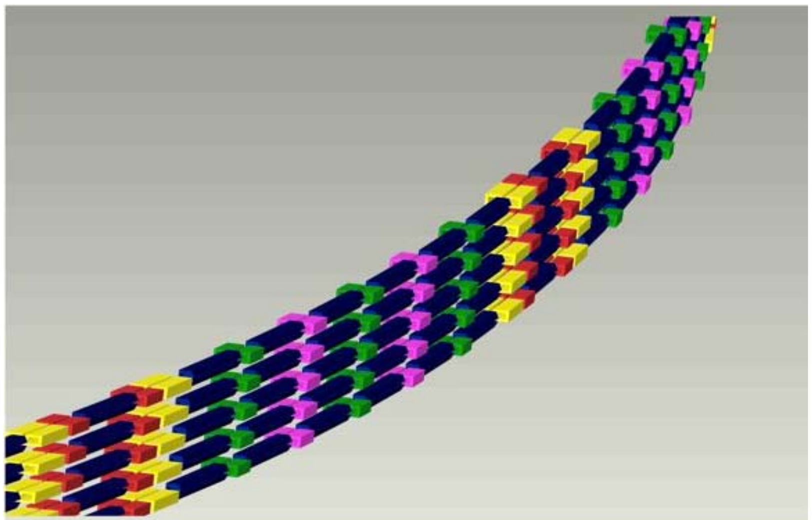
e- beam parameters for FEL



	Soft X-Ray	Hard X-Ray
Energy, GeV	1.8	10
Bunch charge (nC)	0.2	0.2
RMS bunch length (ps)	1	1
RMS energy spread (keV)	50-200	500
RMS ε_n (μm)	0.6	0.2
Undulator period (cm)	1.85	3
Λ0 (nm)	1	0.1

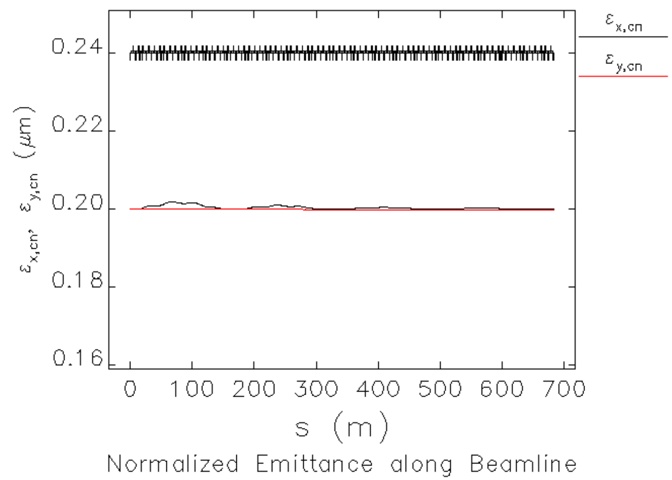
Beam current is kept low (~ 40 Amps) so beam quality is not degraded by CSR in ARCs.

eRHIC ARC and emit preservation

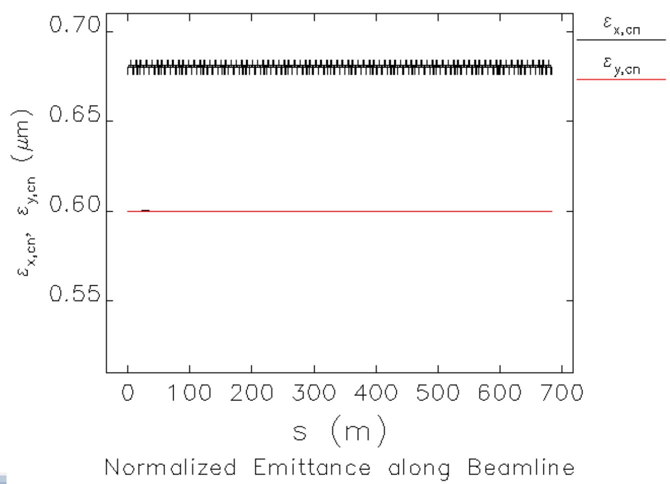


E_{beam} (GeV)	30
L_{dip} (m)	3.12
B_0 (T)	0.4798
$K_{quad}L$(T/m)	28.96

Courtesy of D. Trbojevic

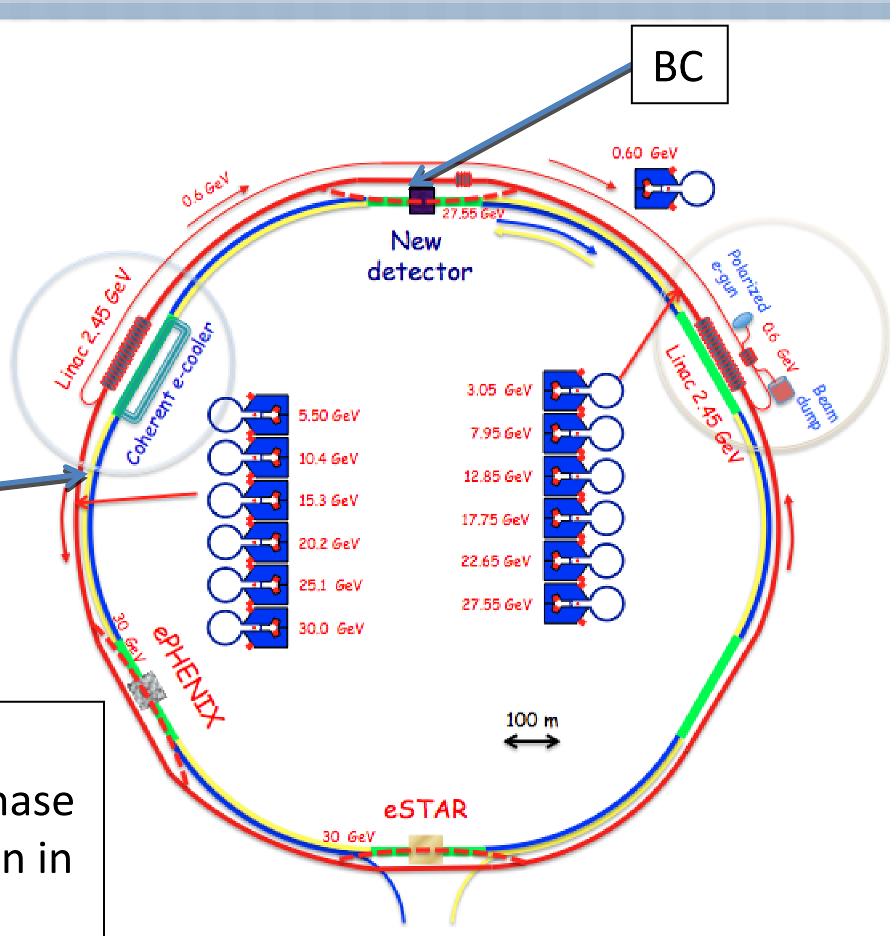


HXR



SXR

Bunch compressor for eRHIC FEL



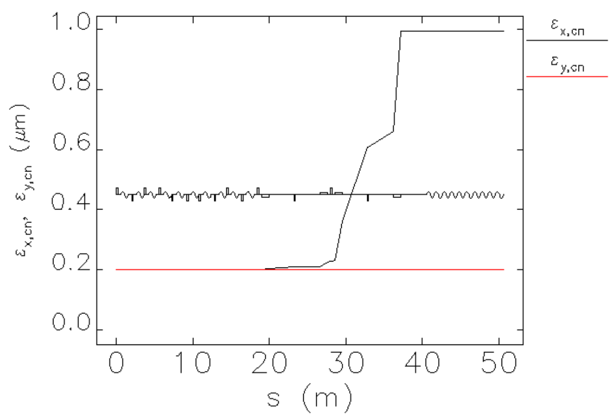
Compress the 2^{nd} pass e-beam @ 12 o'clock.

Beam extraction

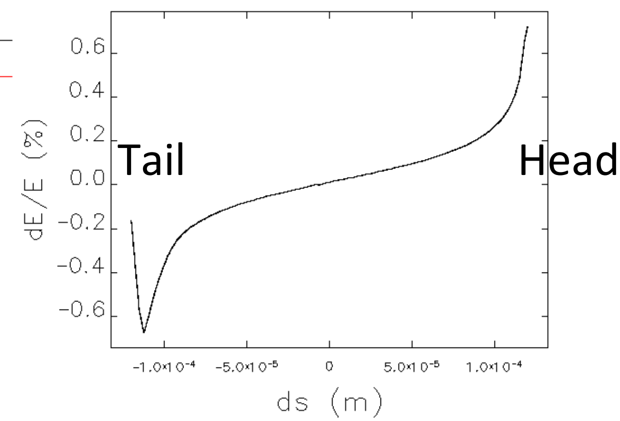
Use the linac @ 2 o'clock as chirping cavity and the linac @ 10 o'clock as energy spread compensator.

BC at single fixed energy to avoid phase space deterioration in circular passes.

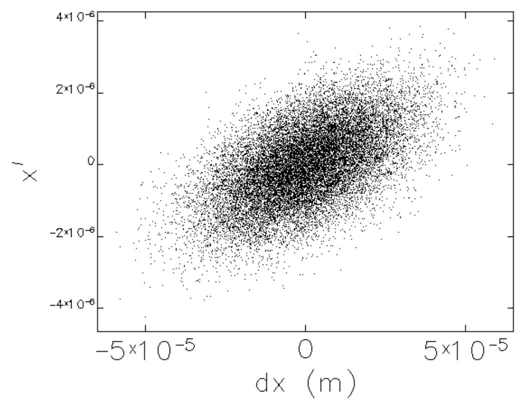
Single stage C-type BC



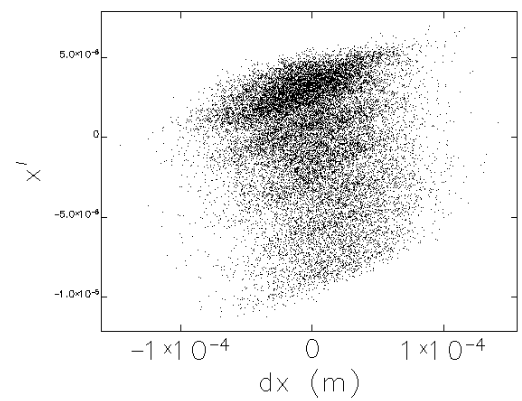
Normalized Emittance along Beamline



Final longitudinal phase space



Before Bunch Compressor



End of Bunch Compressor

Emittance is blown up in C-shape BC 5-fold by Coherent Synchrotron Radiation (CSR).

The coordinate and the angular displacement depending on longitudinal position of the particle result in a smearing in the transverse phase space.

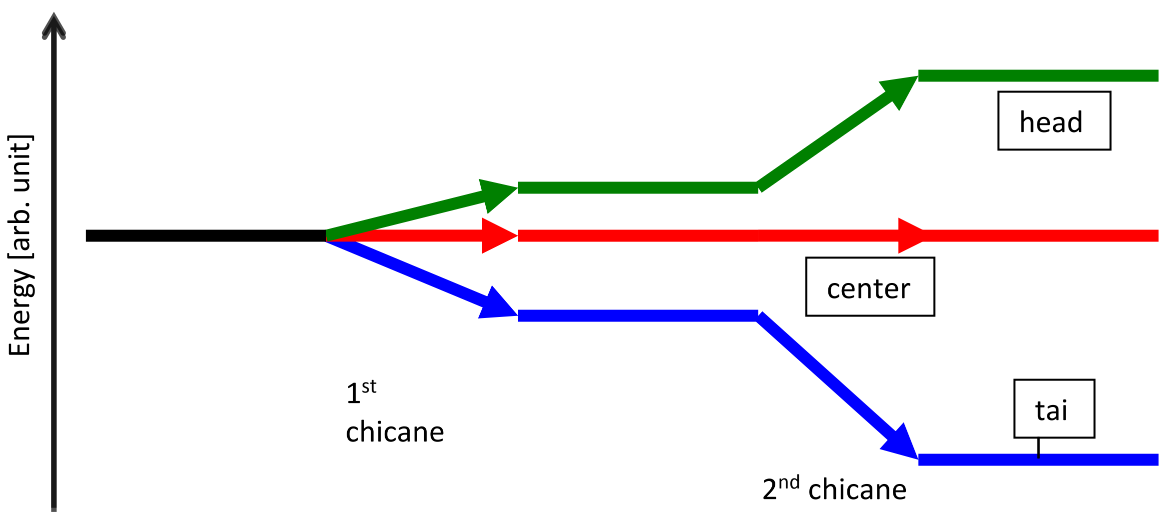
How to solve?

Cure – two chicanes

Using two chicanes with opposite bending directions (thus opposite) D and D’, it is possible to compensate the emittance growth by cancelling the transverse effects induced by CSR wakes.

Change in energy in second chicane is stronger due to stronger wakes – shorter bunch length, thus the bending strength should be smaller.

Beam energy change diagram along the beam line:

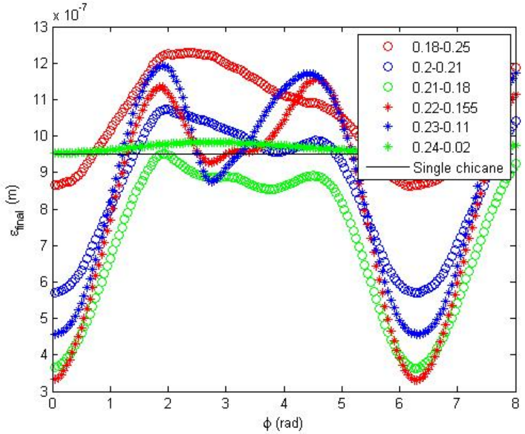


Phase advance between two chicanes can be tuned to realign different longitudinal slices – reduce the overall projected emittance.

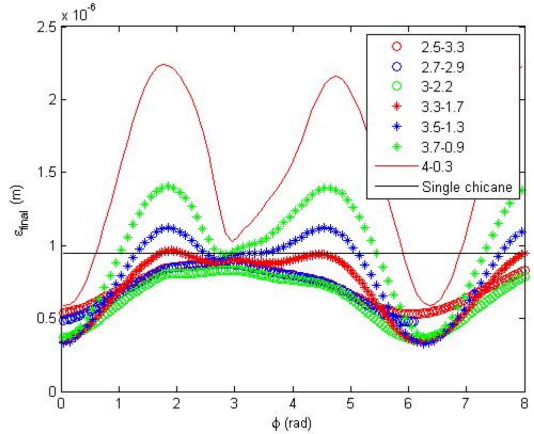
Phase and strengths scan

We scan through the phase advance, the bending angles of the two chicanes and drift lengths between dipoles:

Drifts (3.5 -1.3) are fixed



Angles (0.22 – 0.155) are fixed



Optimal phase advance is 6.05 rad.

Optimal ratio in strengths (R_{56}) of two chicanes is 4:1.

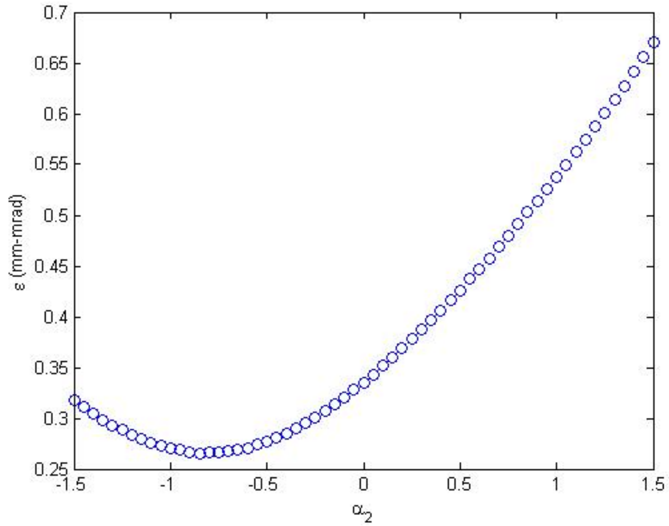
Single chicane's final emittance is shown as a baseline. Best parameter set reduces the emittance growth to about 60%.

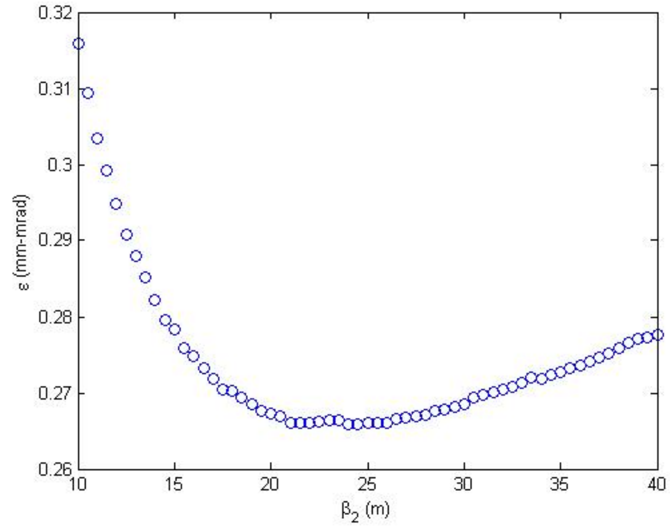
Optics scan

We also scan thru the optics functions (β, α) @ 2nd chicane:

Fix beta, change alpha

Fix alpha, change beta

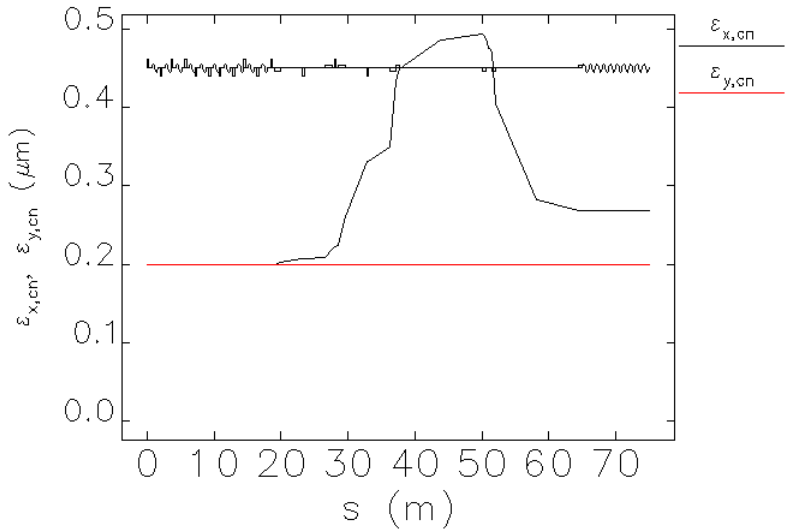




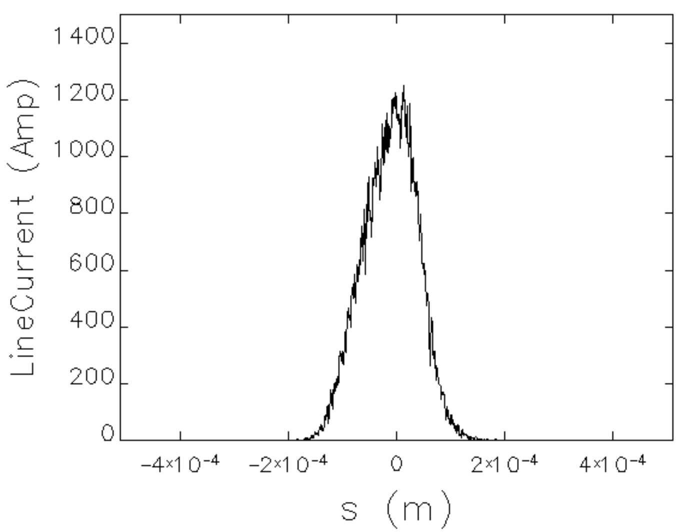
Alpha function has stronger effect than beta function and the optimal point has a emittance growth of about 30%.

Zigzag chicane performance

After scanning all parameters (chicane strengths, optics and phase advance), we largely suppress the CSR induced emittance growth:



Normalized Emittance along Beamline

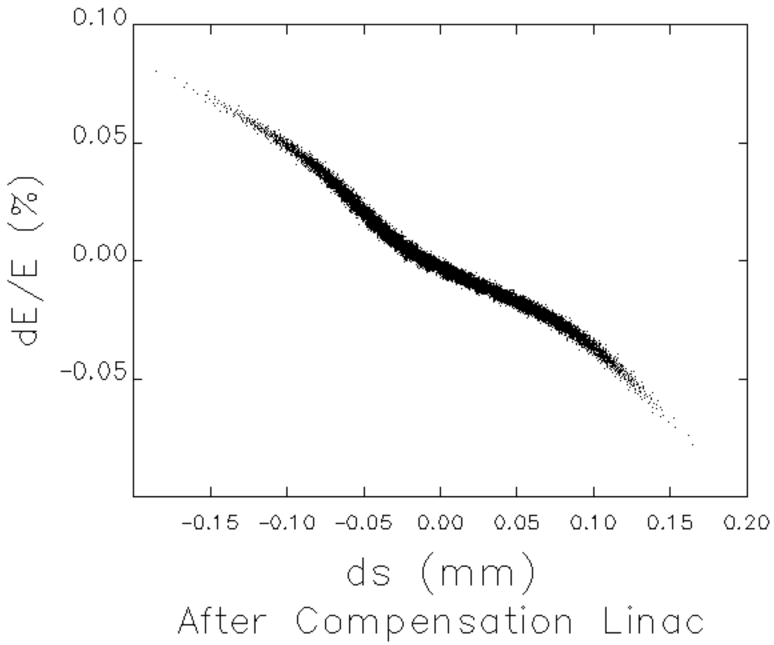


Beam current distribution after 2nd Bunch Compressor

Peak current (~ 1200 Amps) results in a 30 fold compression with CSR suppression scheme.

Beam distribution before FEL

Final longitudinal phase space distribution

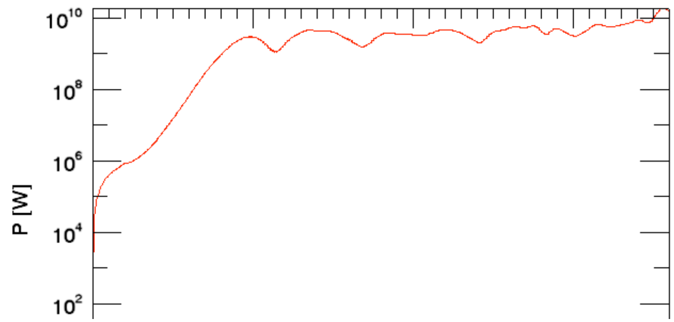


Final beam parameters:

	Soft X-ray	Hard X-ray
E_f(GeV)	1.8	10
Peak current (amp)	600	1200
Projected rms energy spread	1.15e-4	1.77e-4
ε_f (µm)	0.678	0.253

GENESIS 2.0

FEL growth and spectrum

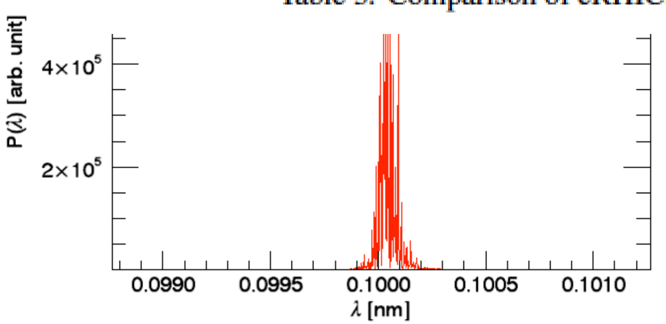


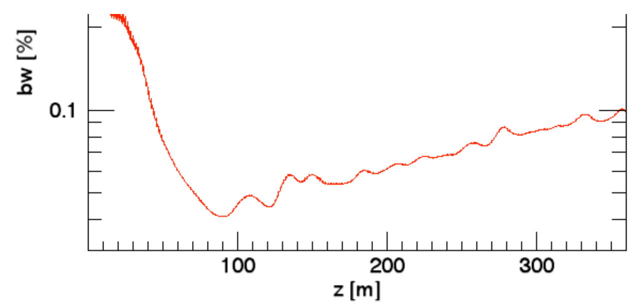
Reaches saturation in 100 m.

Fitted 3D gain length : 2 m.

Parameter	LCLS	SCSS	XFEL	eRHIC,Hard X-FEL	eRHIC, Soft X-FEL
Energy (GeV)	14.35	8	17.5	10	1.8
Rep rate (Hz)	120	60	10	1×10^6	1×10^6
FEL wavelength (Å)	1.2	1	1	1	1×10^3
Peak brightness (ph/sec/mm^2/mrad^2/0.1%BW)	8.5×10^{32}	5×10^{33}	5×10^{33}	$\sim 10^{33}$	$\sim 10^{33}$
Average brightness (ph/sec/mm^2/mrad^2/0.1%BW)	2.4×10^{22}	1.5×10^{23}	1.6×10^{25}	$10^{26} - 10^{29}$	$10^{26} - 10^{29}$

Table 3: Comparison of eRHICs FEL with Projected Performance of X-ray FELs



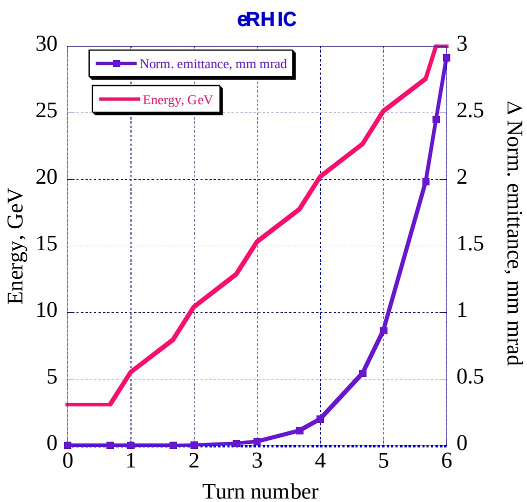


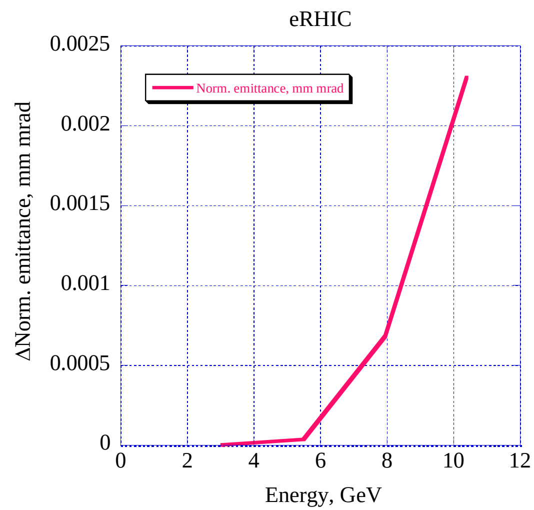
Summary

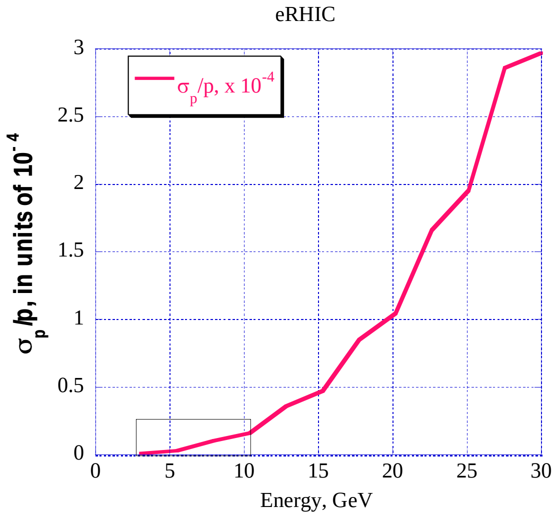
- eRHIC can provide very high quality e- beam which can be used as a perfect platform for FEL.
- We developed a CSR suppression scheme to design a Zigzag type bunch compressor with an order of magnitude lower projected emittance growth than a traditional C-type chicane.
- FEL performance with this e- beam seems promising.

Backup slides

Beam parameters for eRHIC FEL



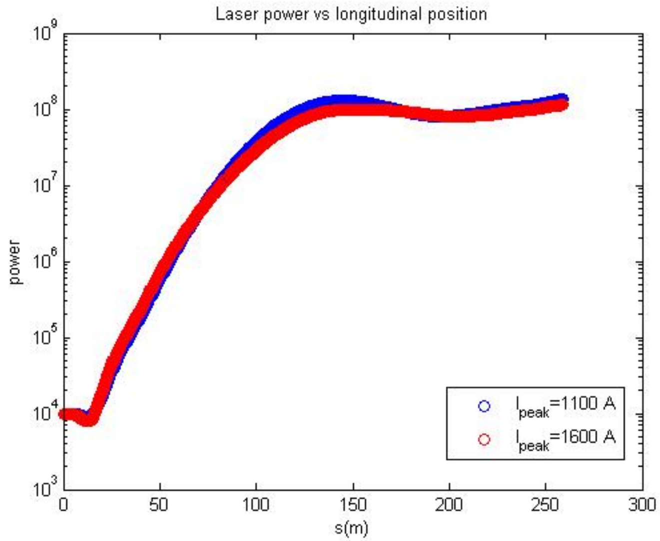




Choose low energy (~ 10 GeV) for FEL to avoid severe blow up in both emittance and energy spread caused by synchrotron radiation. Normalized emittance is largely depend on the injector and assumed to be 0.2 μm in simulation.

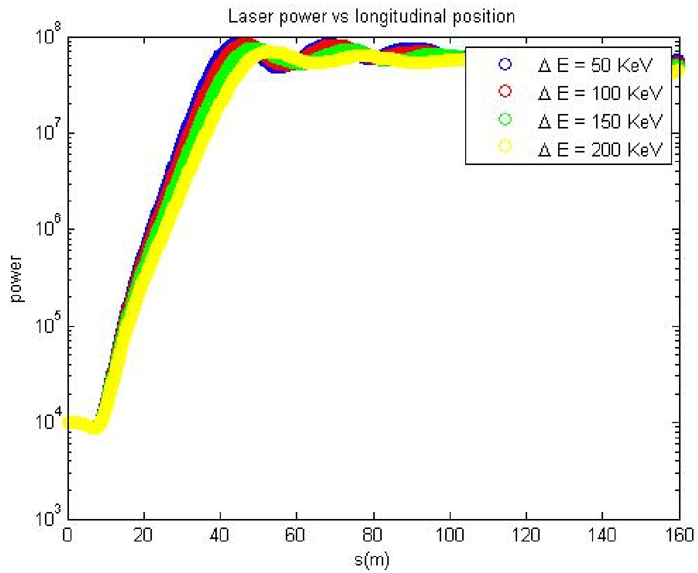
Peak current for FEL

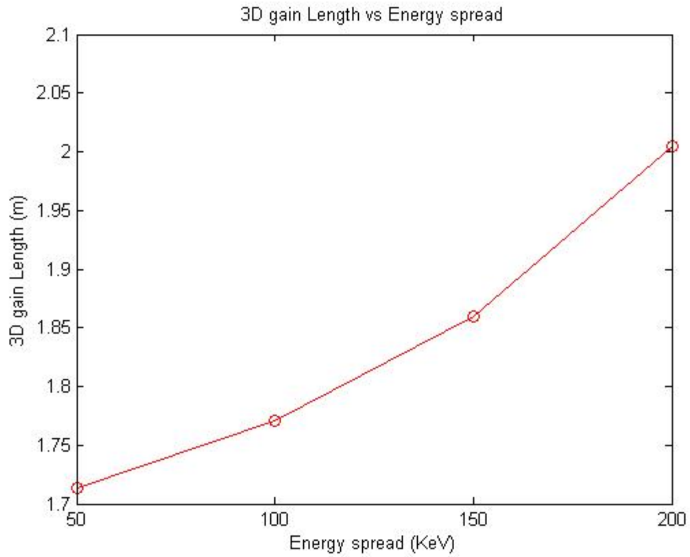
Full rotation would certainly increase the peak current. However, it would also induce a larger correlated energy spread which is hard to compensate downstream. Not to mention the magnified CSR effect. Thus a relative low (~1 kA) beam current is preferable for our implementation.



Energy spread for FEL

By tuning the injector, we should have the ability of tuning the e- beam's energy spread at FEL. Larger energy spread lowers the final lasing power as well as lengthens FEL gain length thru FEL parameter ρ_{FEL}.





R_{56} vs bend angle

Under small angle approximation, using trigonometry, we can prove relation

$$R_{56} = -L\theta^2 - L_{dip}\theta^2 + O(\theta^4)$$

L is the drift length between dipole 1-2 and θ is the bending angle of a dipole. The first term is the path difference in drift space, and second term the path difference in dipoles.

For our case, the small angle is approximation no longer valid thus the result deviates from square relation a bit