BROOKHAVEN NATIONAL LABORATORY

Collider-Accelerator Department

ERL as FEL driver

Yichao Jing, BNL
Vladimir N. Litvinenko, SBU/BNL
6/10/2015
Stony Brook University, NY

ERL'15

Outline

Existing(ed) ERL-FELs

- Jefferson Lab, USA
- ALICE, UK
- BINP, Russia
- JAERI, Japan

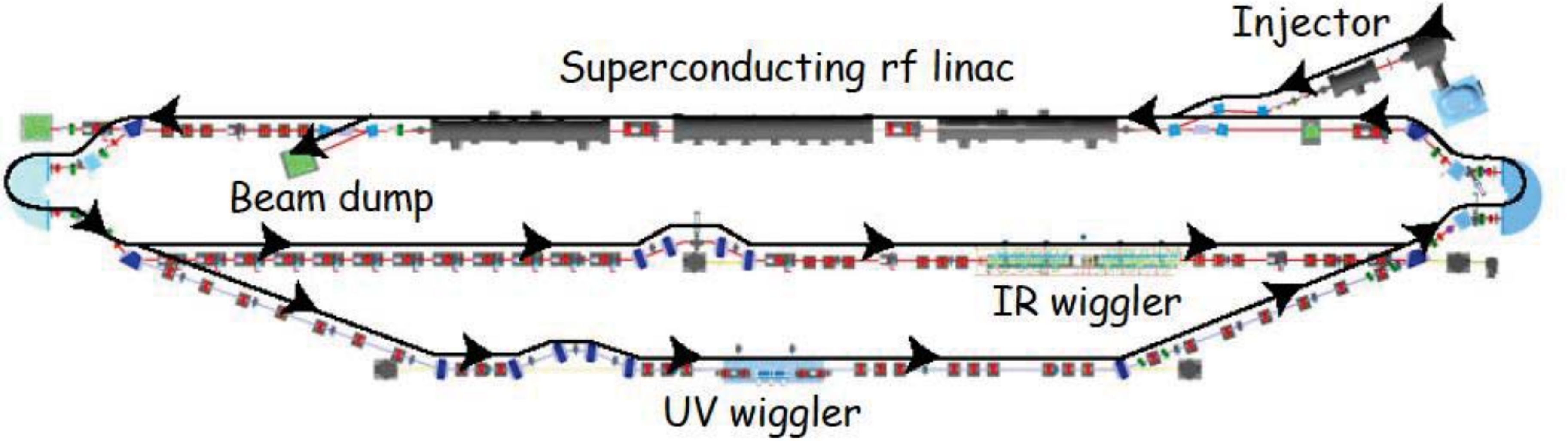
Move further – X-Ray ERL FELs!

- ARC compression
- Zigzag with CSR compensation

Better temporal coherence -- New Ideas?

- XFELO
- OFFELO

JLab IR and UV FEL

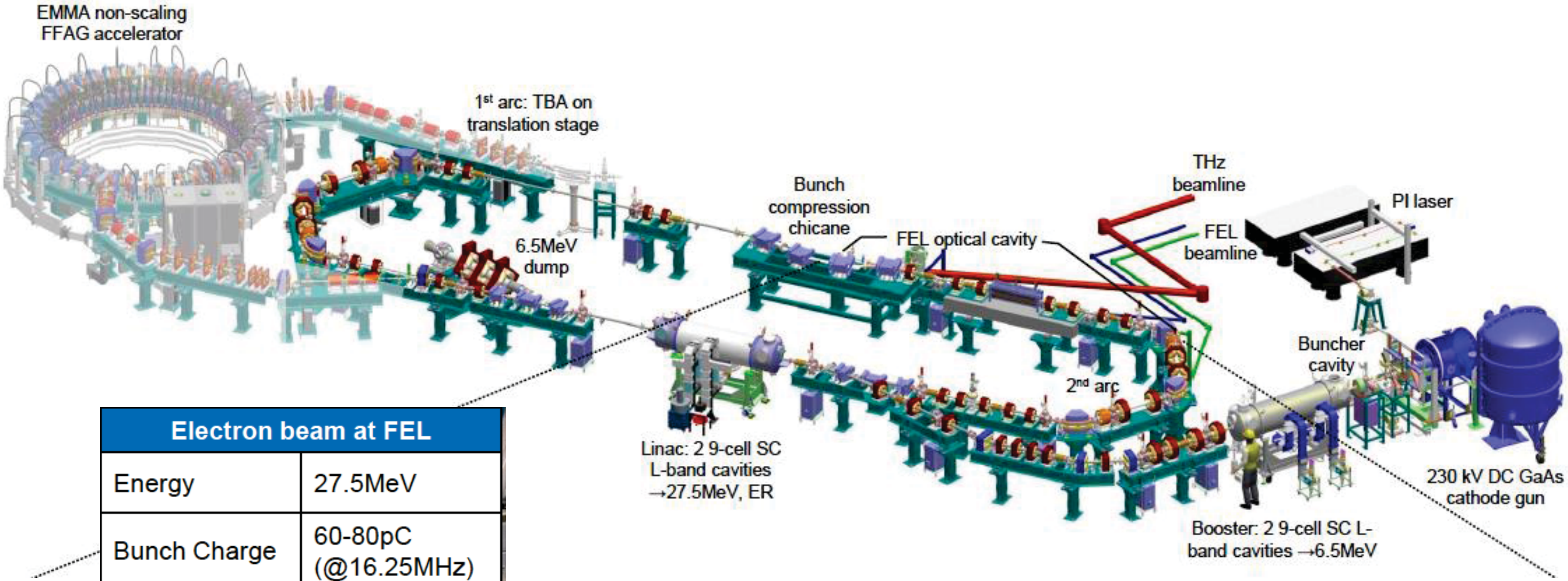


Output Light Parameters	IR	UV
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser power / pulse (microJoules)	100 - 300	25
Laser power (kW)	>10	> 1
Rep. Rate (cw operation, MHz)	4.7 – 75	4.7 – 75

Electron Beam Parameters	IR	UV
Energy (MeV)	80-200	200
Accelerator frequency (MHz)	1500	1500
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50	0.13
Normalized emittance (mm-mrad)	<30	<11
Induced energy spread (full)	10%	5%

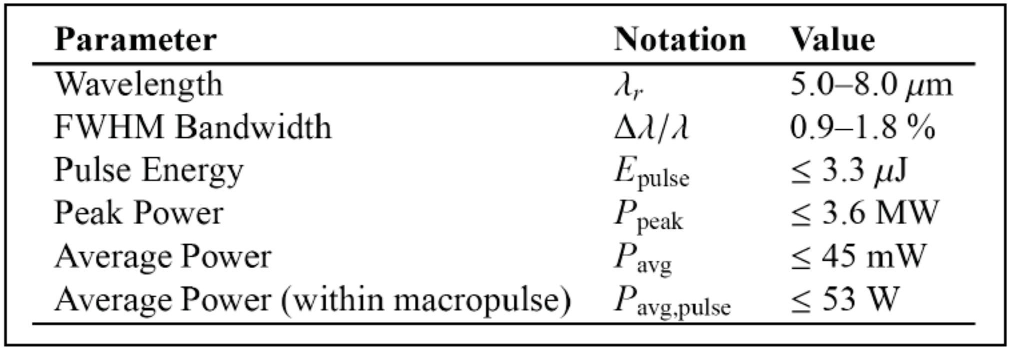
©S. Benson

ALICE ERL FEL



Electron beam at FEL	
Energy	27.5MeV
Bunch Charge	60-80pC (@16.25MHz)
FWHM Bunch Length	~1ps
Normalised Emittance	~12 mm-mrad
Energy Spread	~0.5% rms
Repetition Rate	81.25MHz/ 16.25MHz
Macropulse Duration	≤100μs
Macropulse Rep. Rate	10Hz

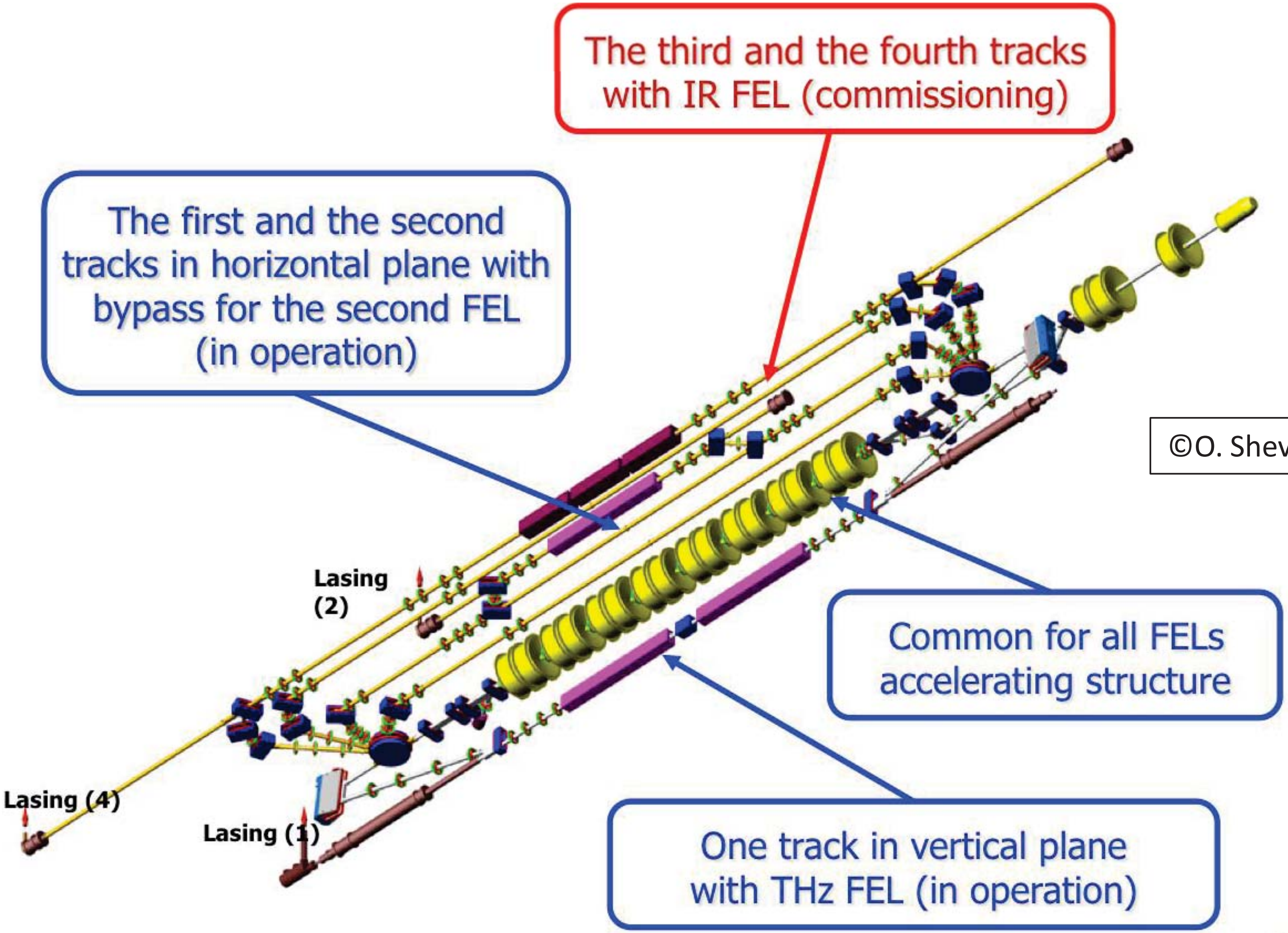
Achieved ALICE FEL output parameters, in-vacuum immediately behind the downstream mirror:



Parameter	Notation	Value
Wavelength	λ_r	5.0–8.0 μm
FWHM Bandwidth	$\Delta\lambda/\lambda$	0.9–1.8 %
Pulse Energy	E_{pulse}	$\leq$ 3.3 μJ
Peak Power	P_{peak}	$\leq$ 3.6 MW
Average Power	P_{avg}	$\leq$ 45 mW
Average Power (within macropulse)	$P_{\mathrm{avg,pulse}}$	$\leq$ 53 W

©D. Dunning

Novosibirsk ERL FEL



The third and the fourth tracks with IR FEL (commissioning)

The first and the second tracks in horizontal plane with bypass for the second FEL (in operation)

Common for all FELs accelerating structure

One track in vertical plane with THz FEL (in operation)

©O. Shevchenko

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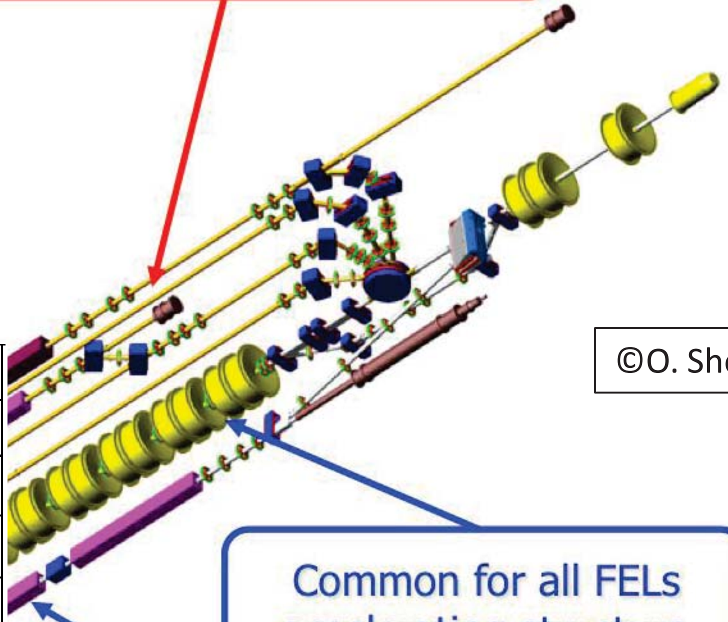

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©O. Shevchenko

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One track in vertical plane with THz FEL (in operation)

Electron Beam Parameters	
Energy (MeV)	12
Accelerator frequency (MHz)	180
Charge per bunch (pC)	900
Average current (mA)	20
Peak Current (A)	10
Beam Power (kW)	240
Energy Spread (%)	0.2
Normalized emittance (mm-mrad)	20

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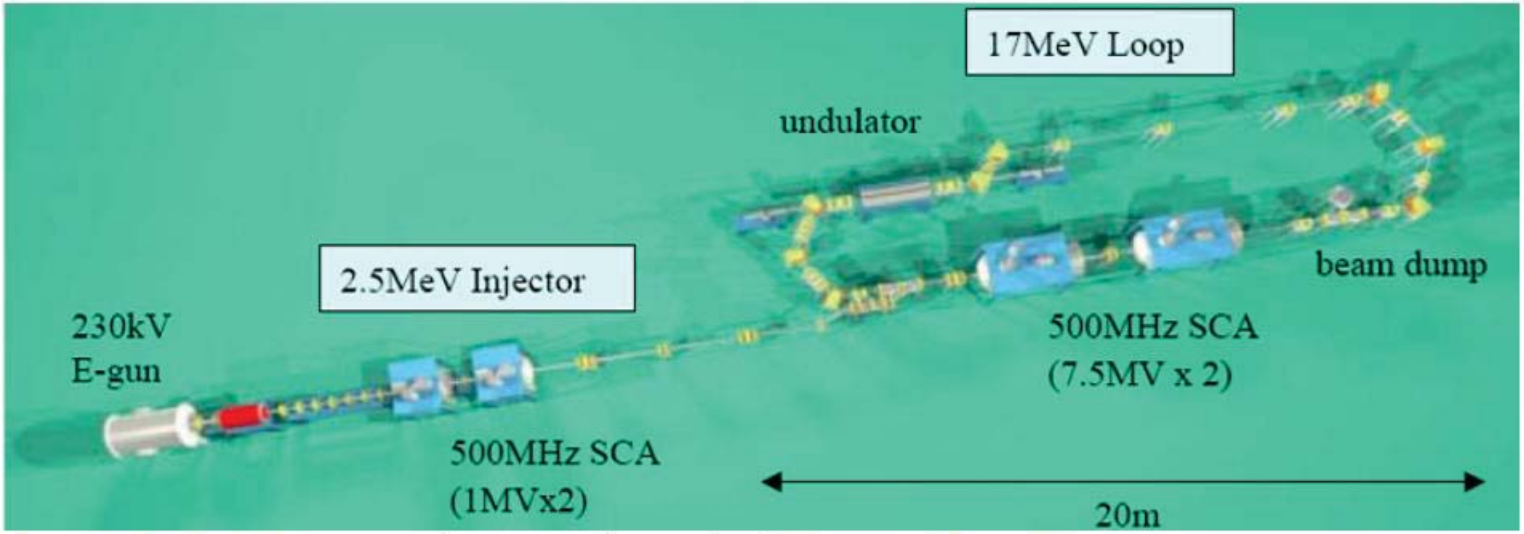
The 1st stage FEL radiation parameters

Radiation wavelength, mm	0.12 - 0.24
Pulse duration, ps	70
Repetition rate , MHz	11.2
Maximum average power, kW	0.5
Minimum relative linewidth (FWHM)	$3\cdot10^{-3}$
Peak power, MW	1

The obtained radiation parameters are still the world record in terahertz region.

JAERI ER-FEL



Output Light Parameters	Achieved	Goal
Wavelength range (microns)	22	22
Bunch Length (FWHM psec)	15	6
Laser power / pulse (microJoules)	10	120
Laser power (kW)	0.1	10
Rep. Rate (MHz)	10.4	83.2
Macropulse format	10ms 10Hz	CW

Electron Beam Parameters	Achieved	Goal
Energy (MeV)	17	16.4
Accelerator frequency (MHz)	500	500
Charge per bunch (pC)	500	500
Average current (mA)	5	40
Peak Current (A)	33	83
Beam Power (kW)	85	656
Energy Spread (%)	~0.5	~0.5
Normalized emittance (mm-mrad)	~40	~40
Induced energy spread (full)	~3%	~3%

©R. Hajima

Advantages of ERL light sources

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Energy efficiency

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In FELs only small portion of electron beam power is converted to laser power – efficiency ~ ρ ~ 1e-2 – 1e-4. Linac based FELs dump the majority of the beam power while ERLs recover the beam energy. Thus makes high repetition rate possible.

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ERL, SR > LINAC

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Beam quality

In storage rings, the beam qualities are determined by equilibrium conditions (dampings, excitations, scatterings…). While in ERL & Linac, fresh electron bunches are used every turn, thus qualities are largely determines by source. This makes short bunches with high peak current and low emittance, energy spread possible.

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ERL is a perfect candidate to provide continuous, high brightness beams.

ERL X-ray light sources

X-ray science evolves towards the new regime: science with coherent X-ray and ultrafast X-rays

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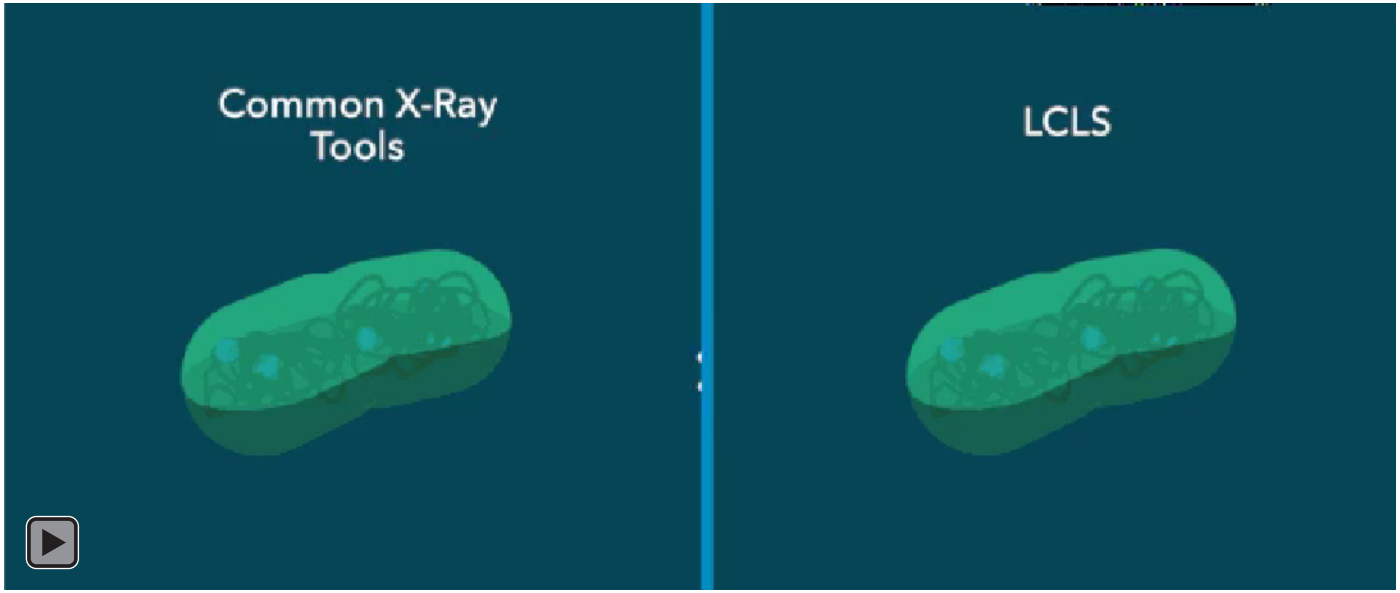

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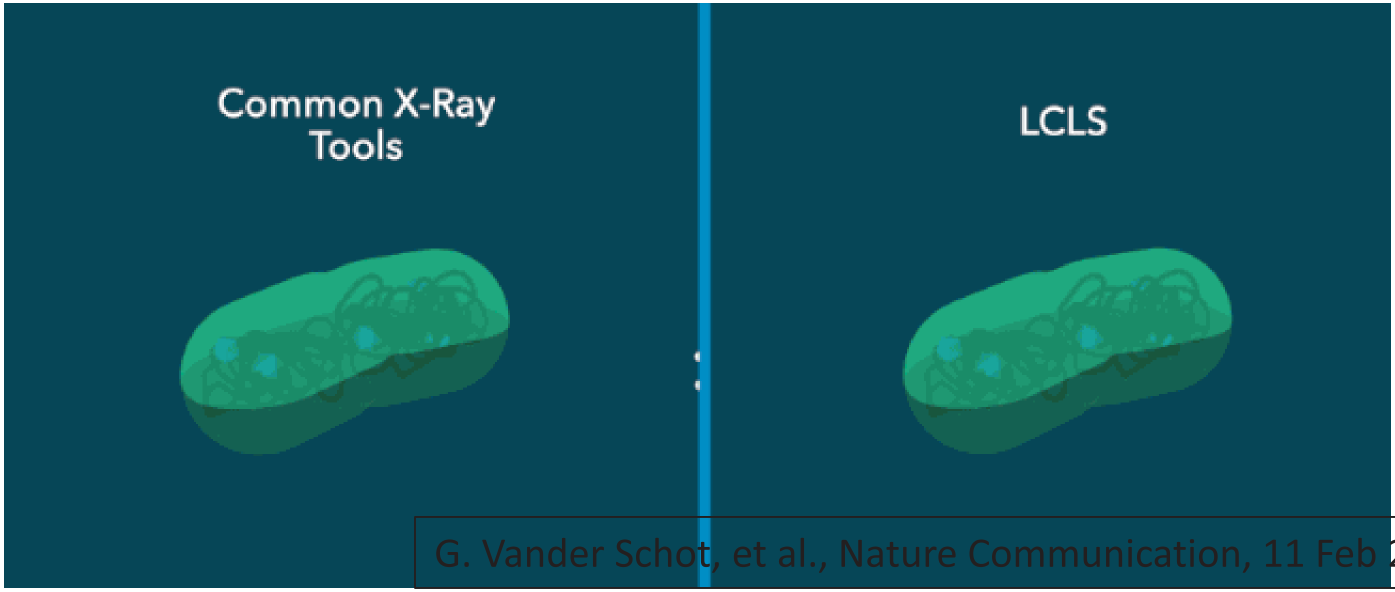

G. Vander Schot, et al., Nature Communication, 11 Feb 2015

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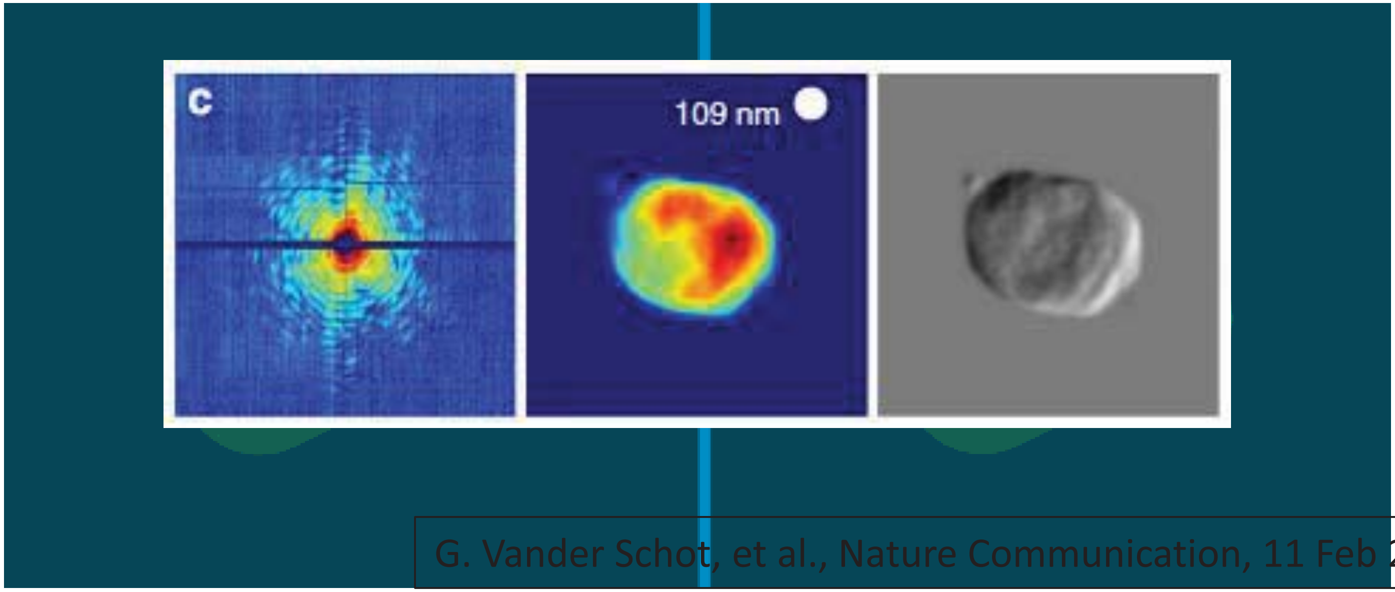

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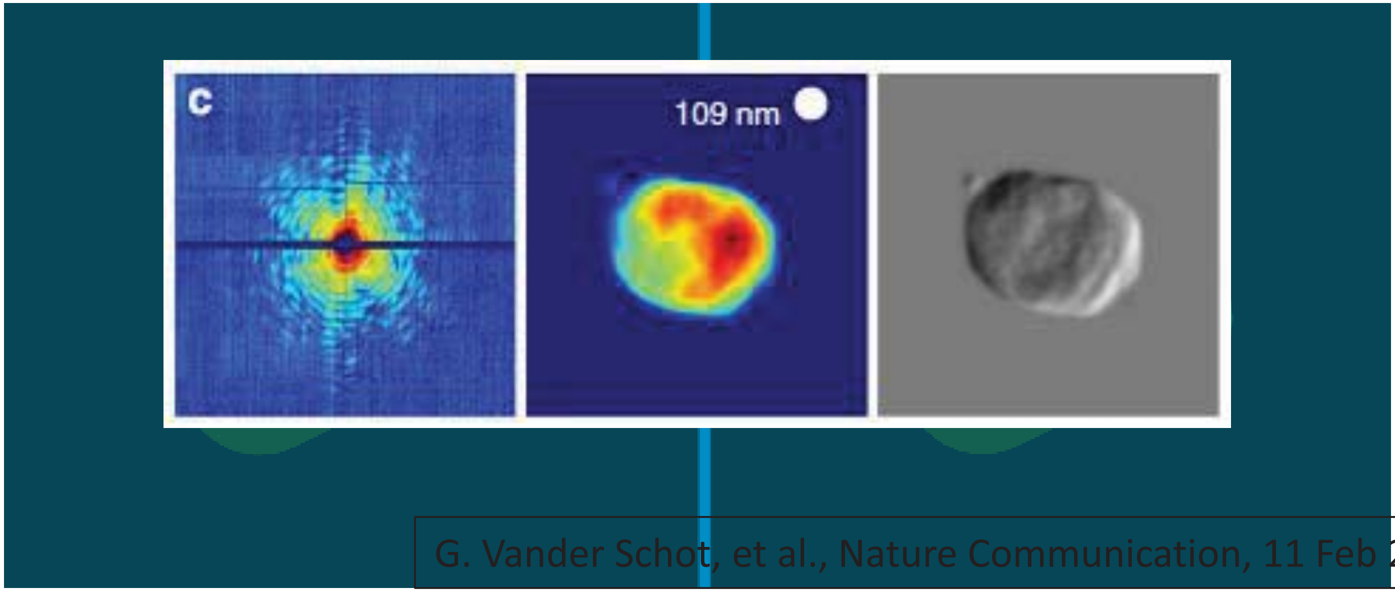

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Higher energy, higher peak current => stronger compression => stronger CSR!

https://www6.slac.stanford.edu/news/2015-02-11-scientists-take-first-x-ray-portraits-living-bacteria-lcls.aspx

Compression in recirculation ARCs

Bunch compression done in ARCs where bends have gradually reduced strengths. So that while the bunch length gets shorter, it experiences weaker bends => less CSR effects!

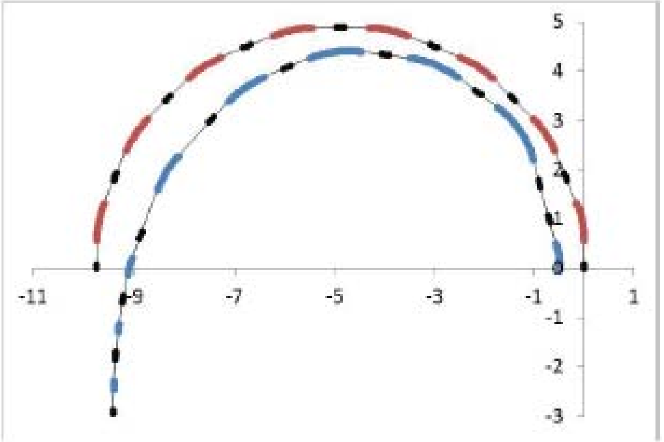
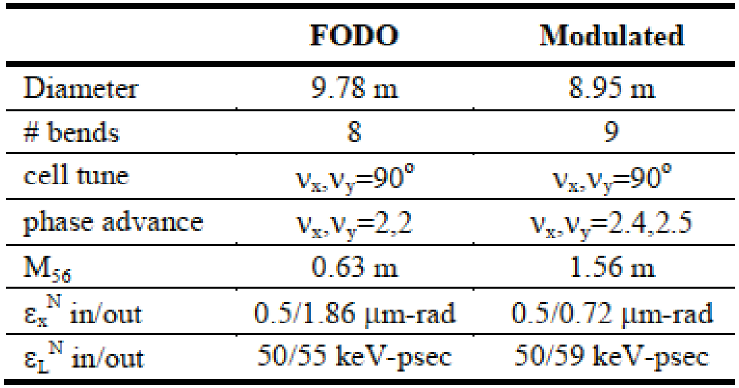


Figure 1: Conventional FO0DO and excitation-modulated compressor layouts. Quadrupoles and beam line in black; conventional line bends in brown, modulated line in blue.

Table 1: Compressor Arc Parameters



	FODO	**Modulated**
Diameter	9.78 m	8.95 m
# bends	8	9
cell tune	$\nu_x,\nu_y=90^\circ$	$\nu_x,\nu_y=90^\circ$
phase advance	$\nu_x,\nu_y=2,2$	$\nu_x,\nu_y=2.4,2.5$
M_{56}	0.63 m	1.56 m
ε_x^N in/out	0.5/1.86 μm-rad	0.5/0.72 μm-rad
ε_L^N in/out	50/55 keV-psec	50/59 keV-psec

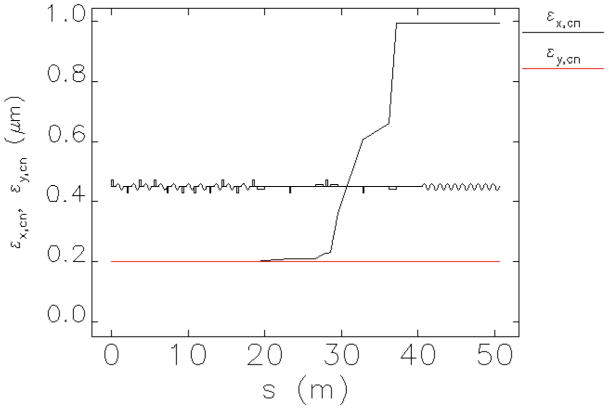
D.R. Douglas, et al., TUPMA034, IPAC15

With sophisticated optics tuning (usually with usage of higher order-poles), smaller emittance growth can be achieved.

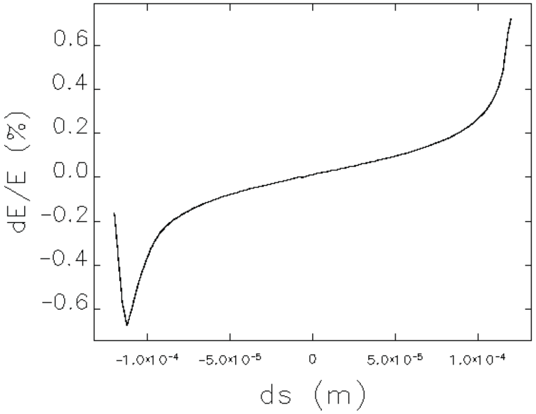
S.Di Mitri, EPL 109, 62002 (2015) and this workshop

Alternative way – “cancel” the CSR!

To the lowest order, the smearing in the transverse phase space is result of the coordinate and the angular displacement depending on longitudinal position of the particle.



Normalized Emittance along Beamline



Final longitudinal phase space

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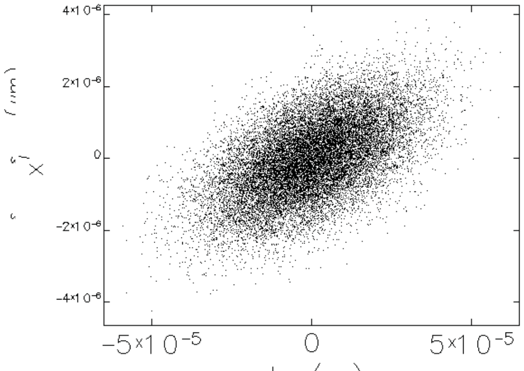
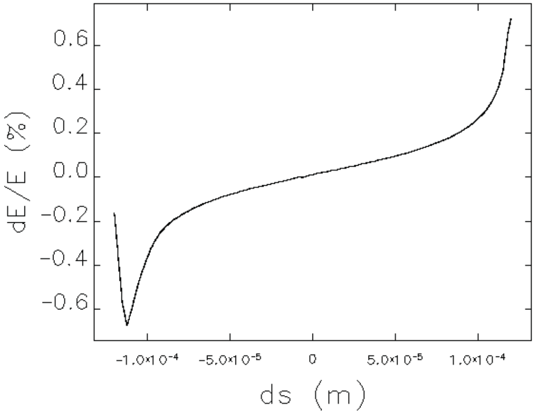


Before Bunch Compressor



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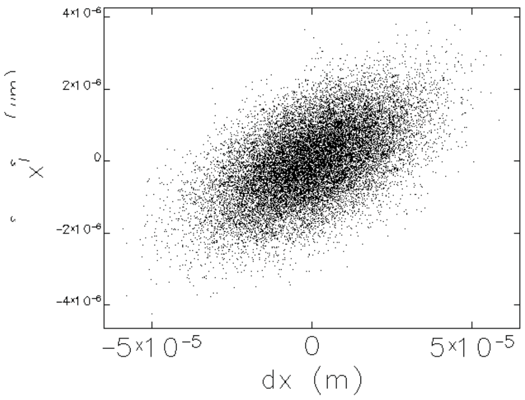

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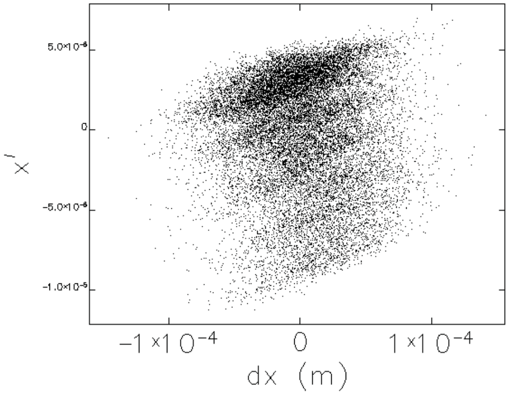

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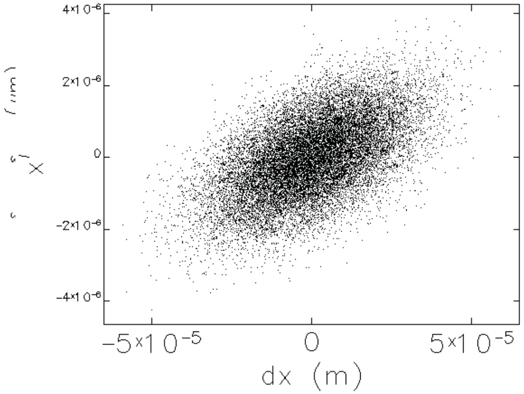

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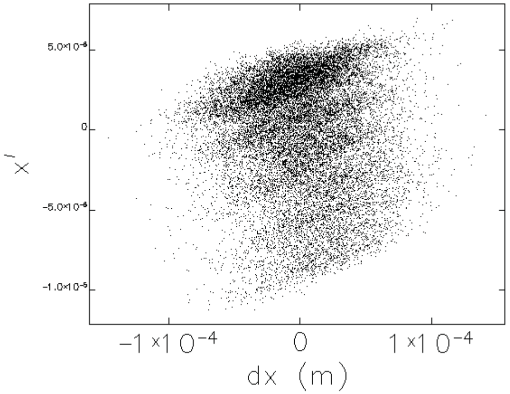

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How to remove this? – negative dispersion!

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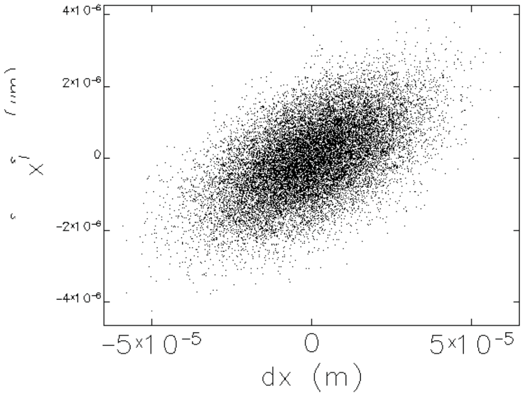

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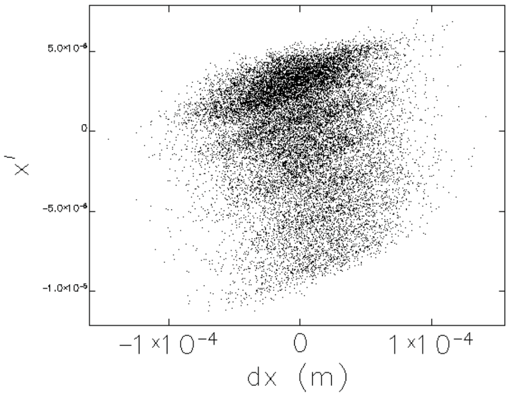

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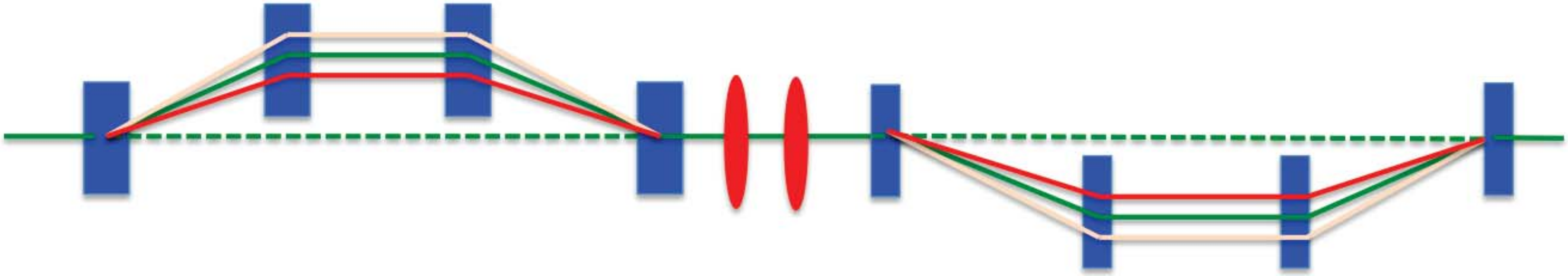

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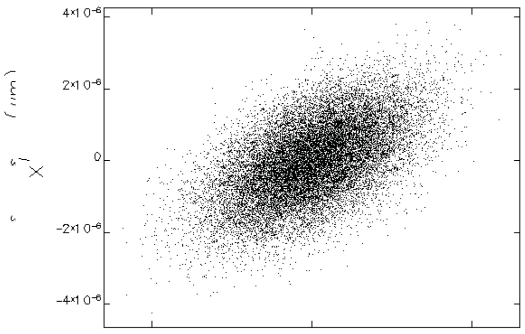

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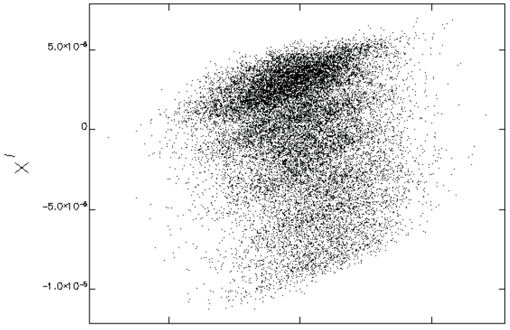

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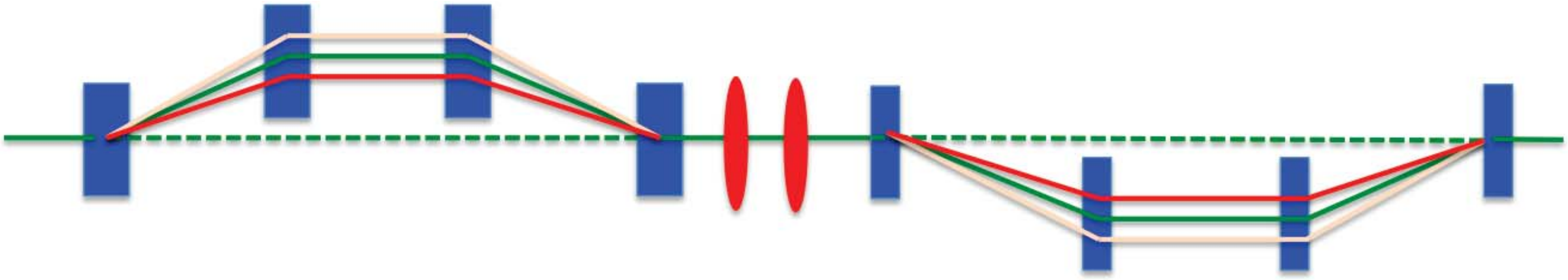
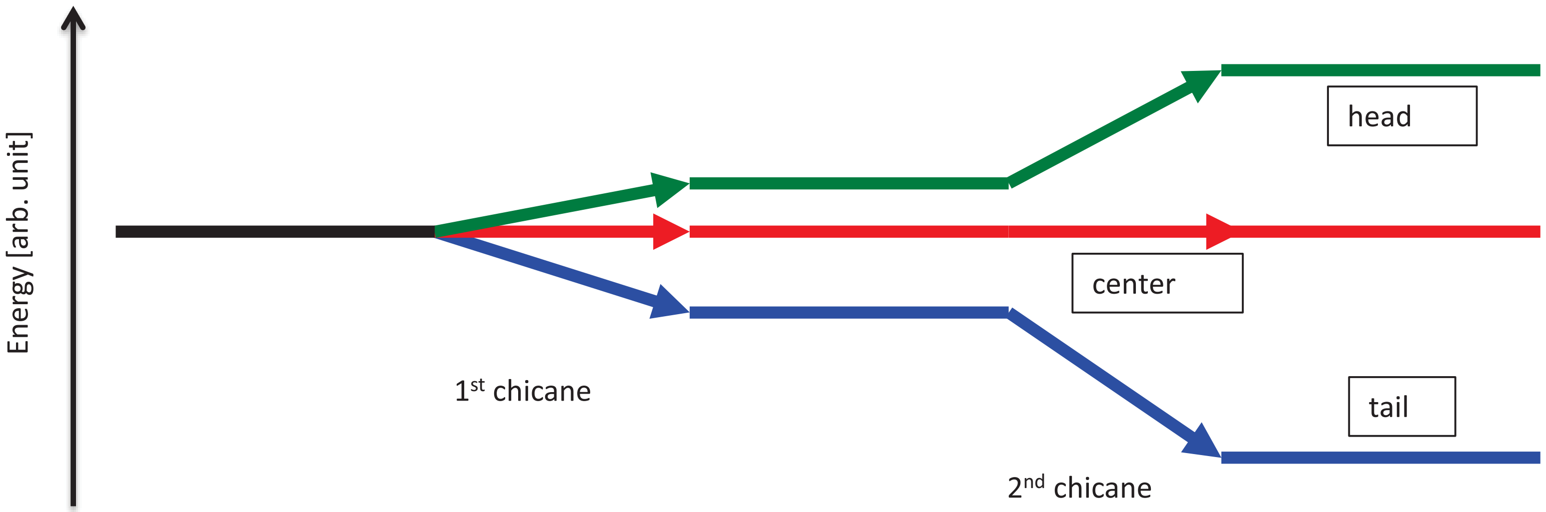


PRSTAB. **16**, 060704(2013)

Zigzag chicane – strengths balancing

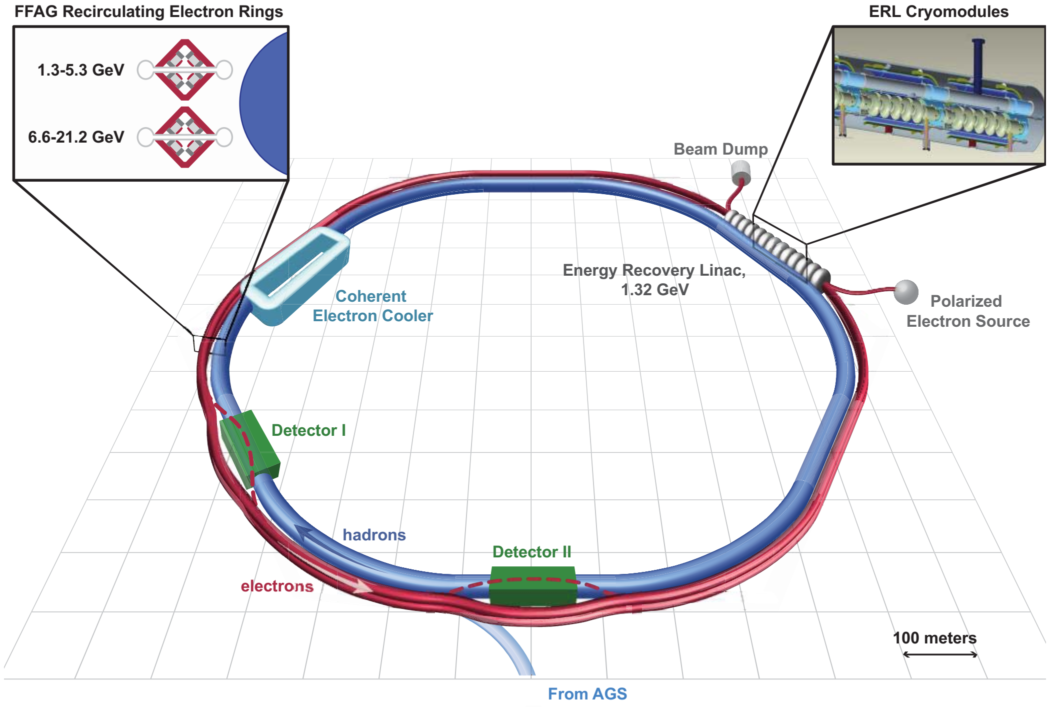
Beam energy change diagram along the beam line:



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

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

Case study – using eRHIC beam for FEL



	Soft X-Ray	**Hard X-Ray**
Energy, GeV	1.8	10
Bunch charge (nC)	0.1	0.1
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

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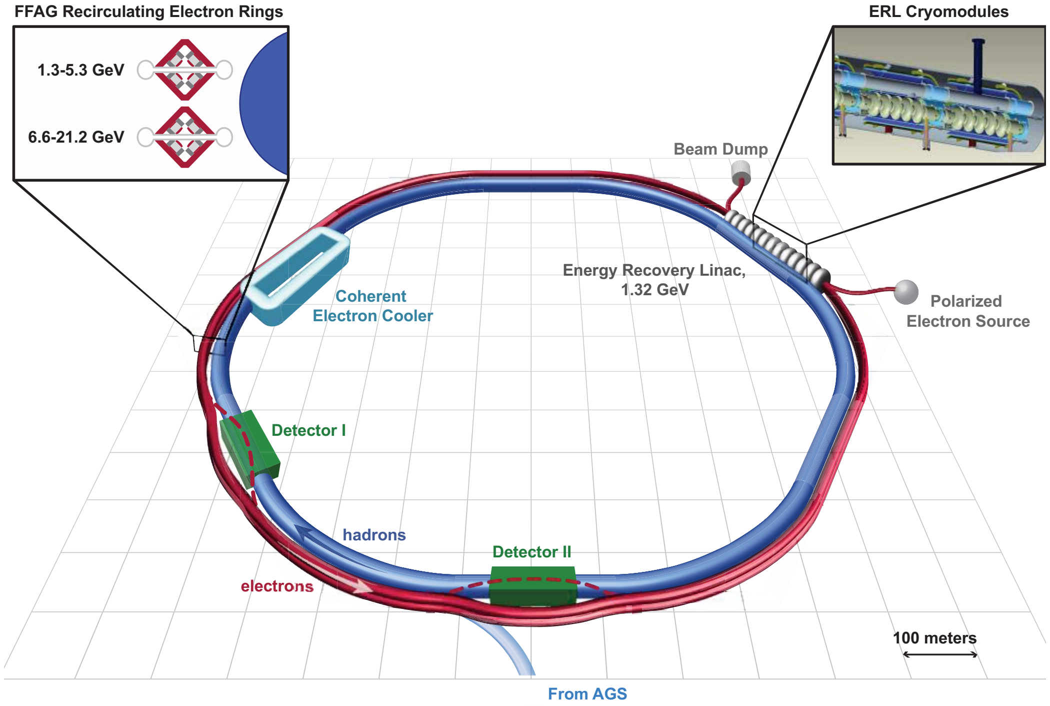

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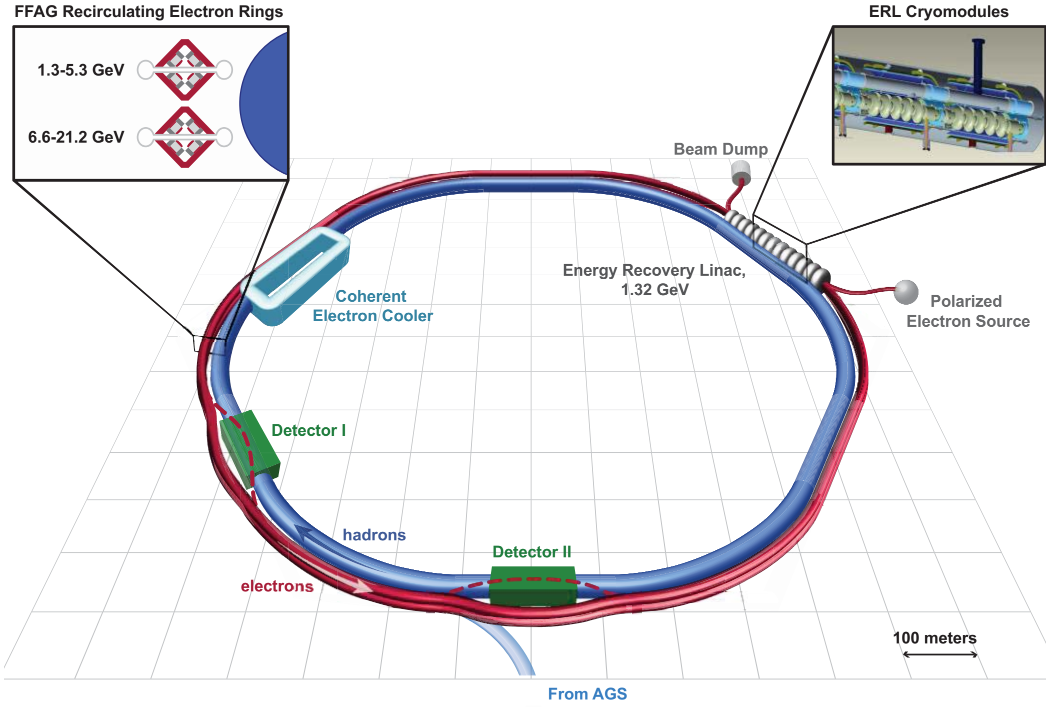

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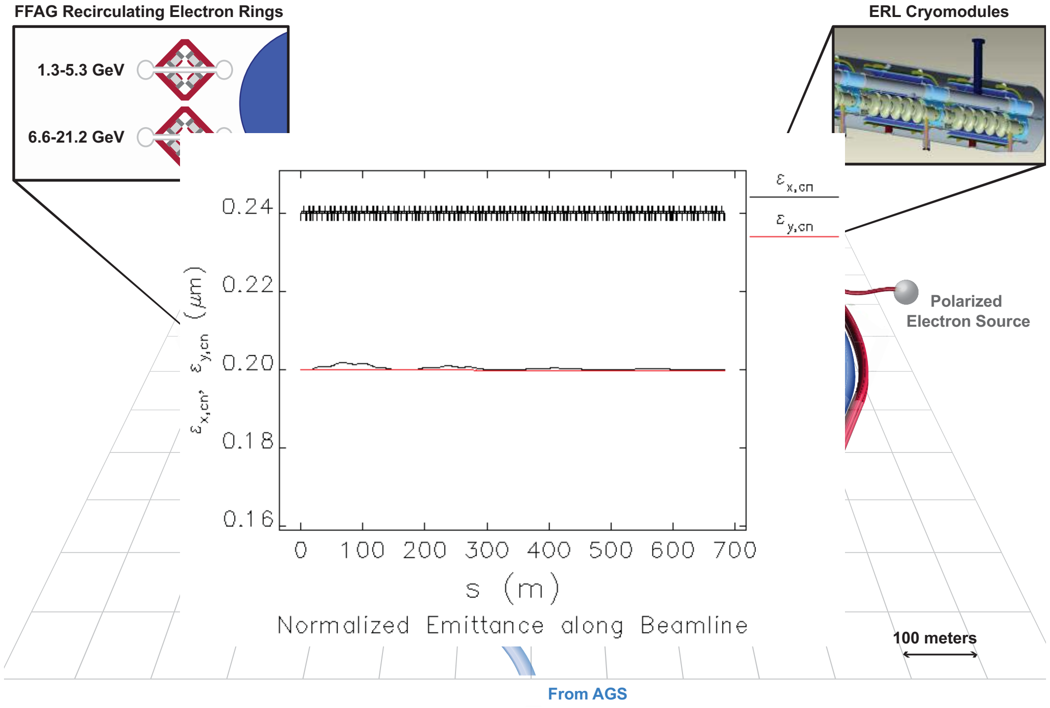

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Zigzag chicane performance

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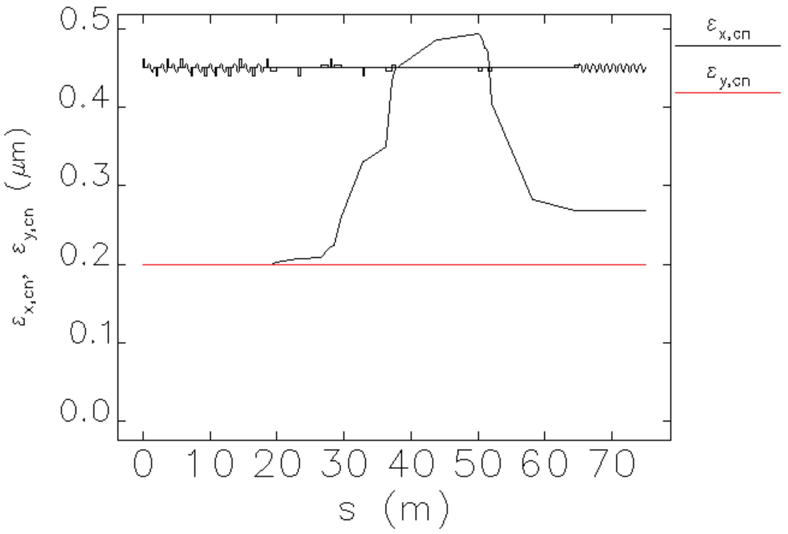
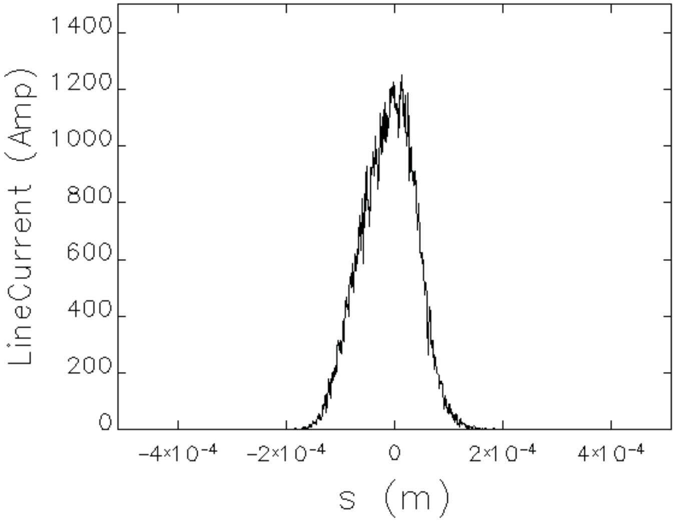


Normalized Emittance along Beamline



Beam current distribution after 2nd Bunch Compressor

MOPMN028, IPAC15

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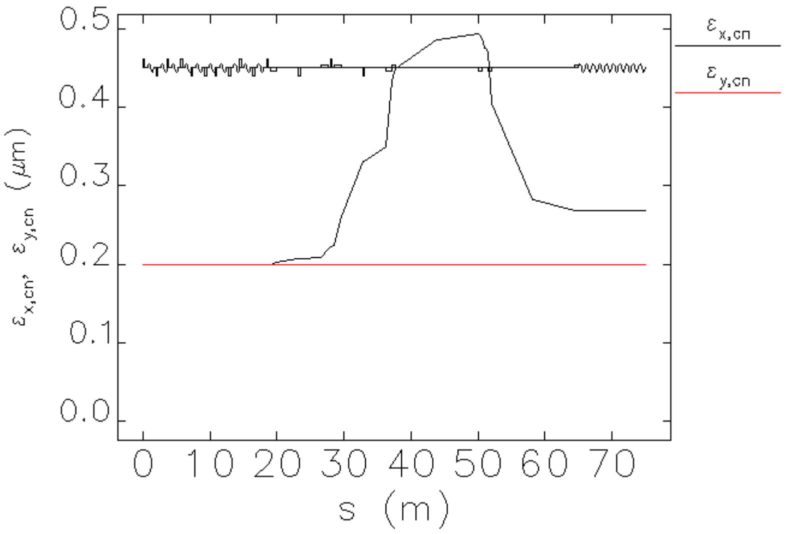

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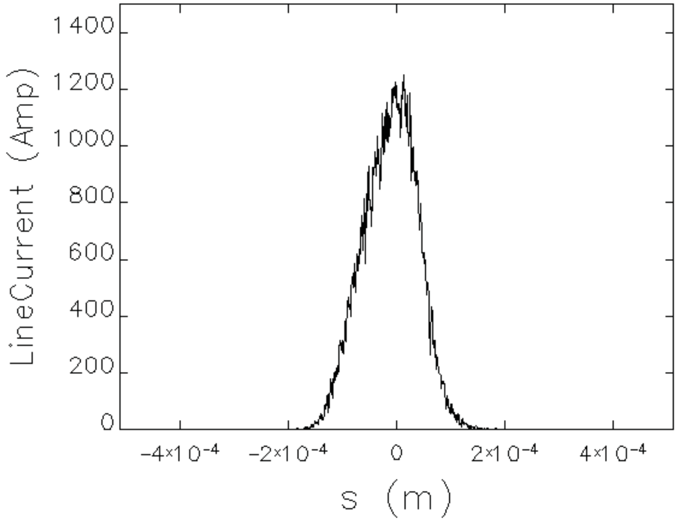


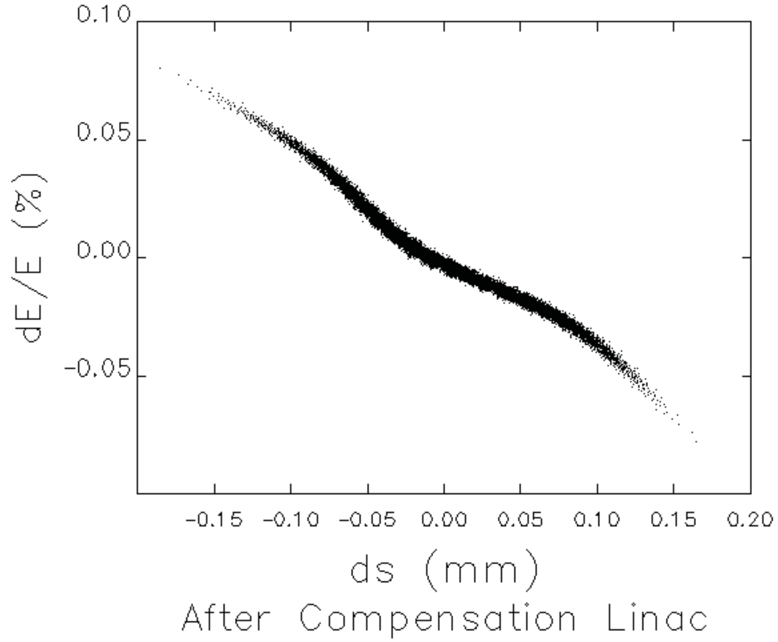
Beam current distribution after 2nd Bunch Compressor

Peak current (~ 1200 Amps) results in a 30 fold compression with CSR suppression scheme. A similar compression scheme has been applied to ATF2 upgrade to generate a 140+ fold compression with ~ 20% emittance growth.

MOPMN028, IPAC15

Beam distribution before FEL

Final longitudinal phase space distribution



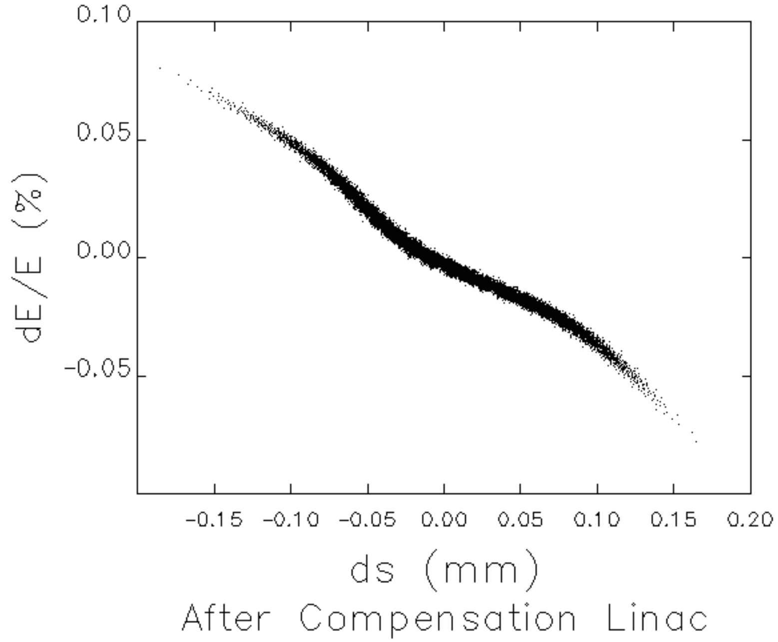
After Compensation Linac

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

Beam distribution before FEL

Final longitudinal phase space distribution



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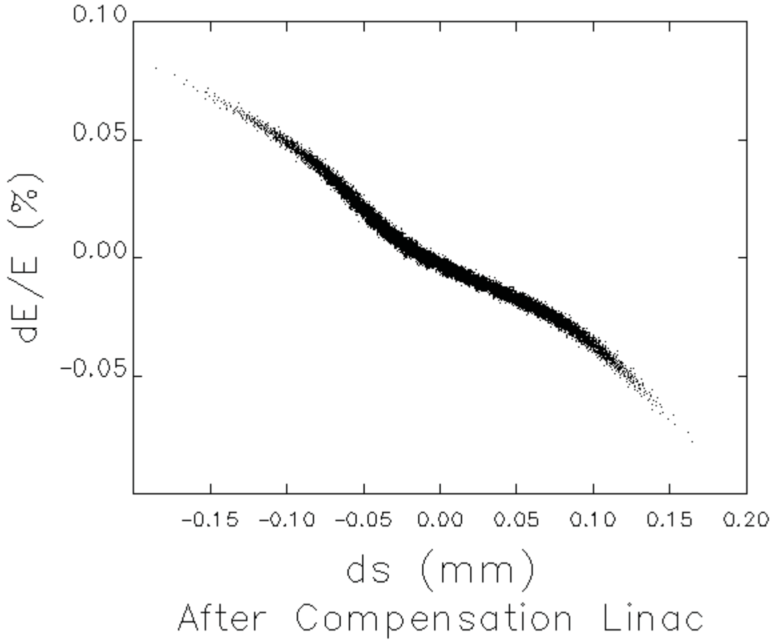
GENESIS 2.0

Beam distribution before FEL

Final longitudinal phase space distribution



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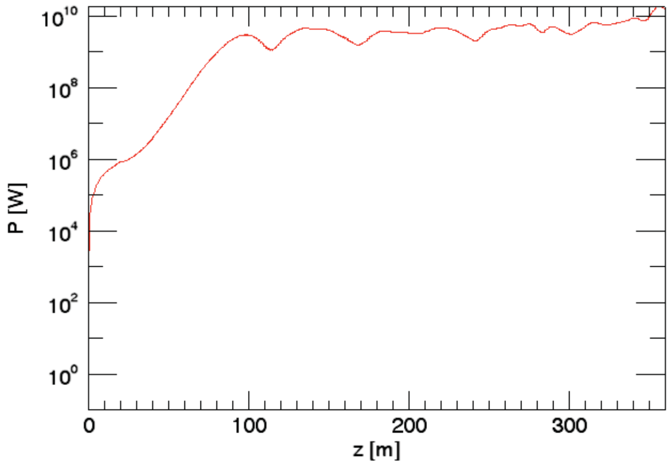
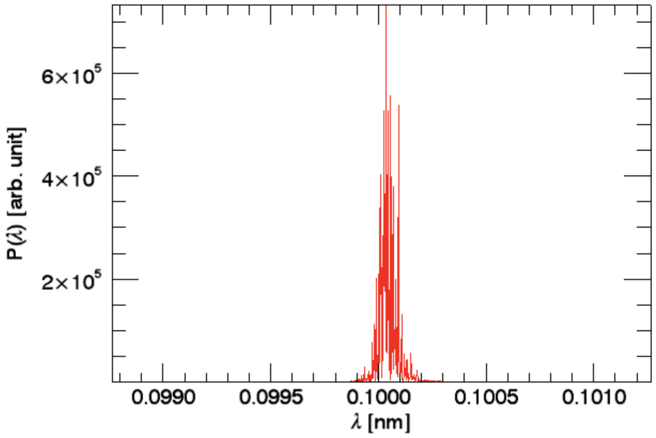
GENESIS 2.0 ➡

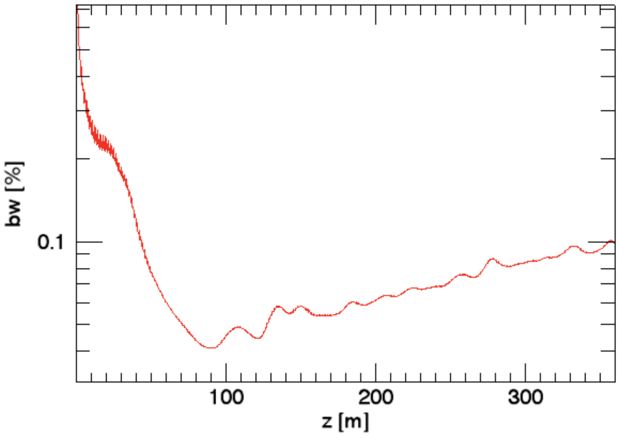
FEL growth and spectrum



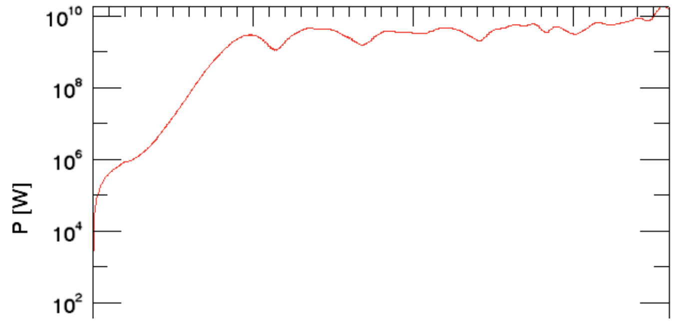
Reaches saturation in 100 m.

Fitted 3D gain length : 2 m.



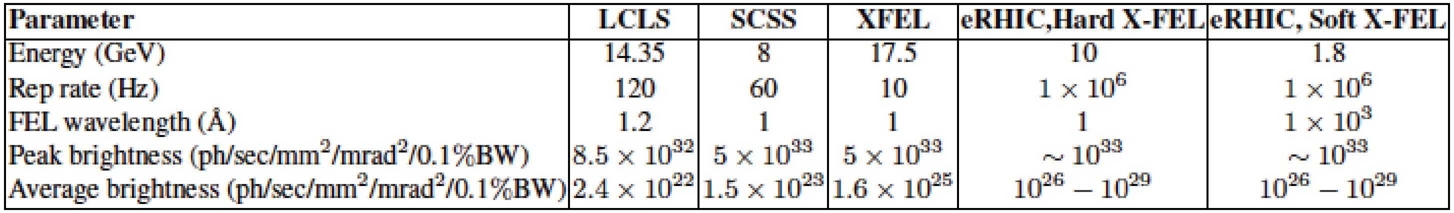


FEL growth and spectrum



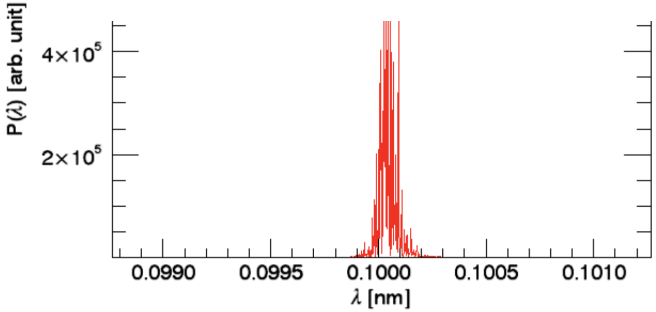
Reaches saturation in 100 m.

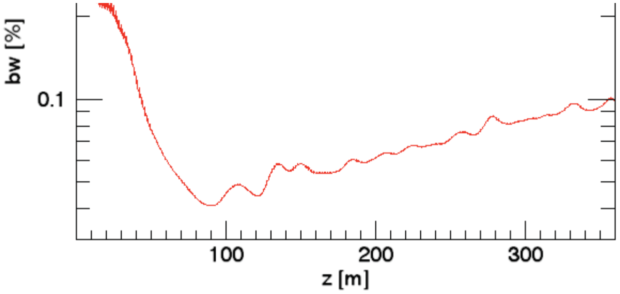
Fitted 3D gain length : 2 m.



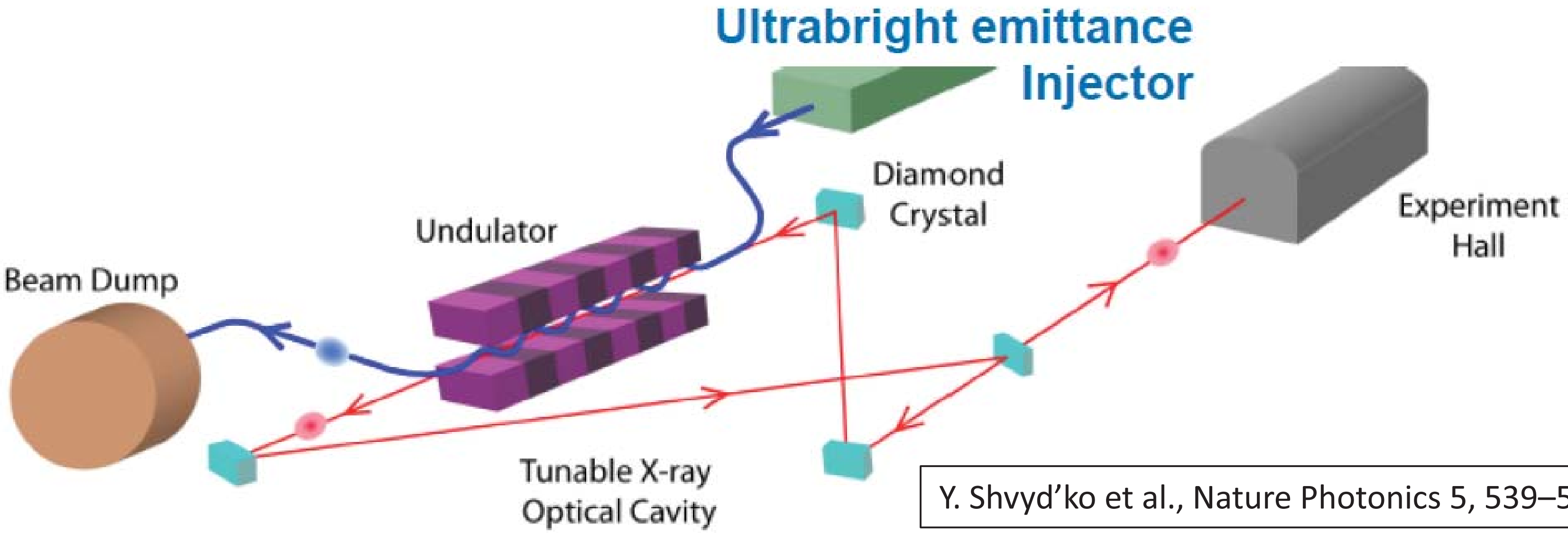
Parameter	**LCLS**	**SCSS**	**XFEL**	**eRHIC,Hard X-FEL**	**eRHIC, Soft X-FEL**
Energy (GeV)	14.35	8	17.5	10	1.8
Rep rate (Hz)	120	60	10	1×10^6	1×10^6
FEL wavelength (Å)	1.2	1	1	1	1×10^3
Peak brightness (ph/sec/mm^2/mrad^2/0.1%BW)	8.5×10^{32}	5×10^{33}	5×10^{33}	$\sim 10^{33}$	$\sim 10^{33}$
Average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





X-Ray FEL oscillator

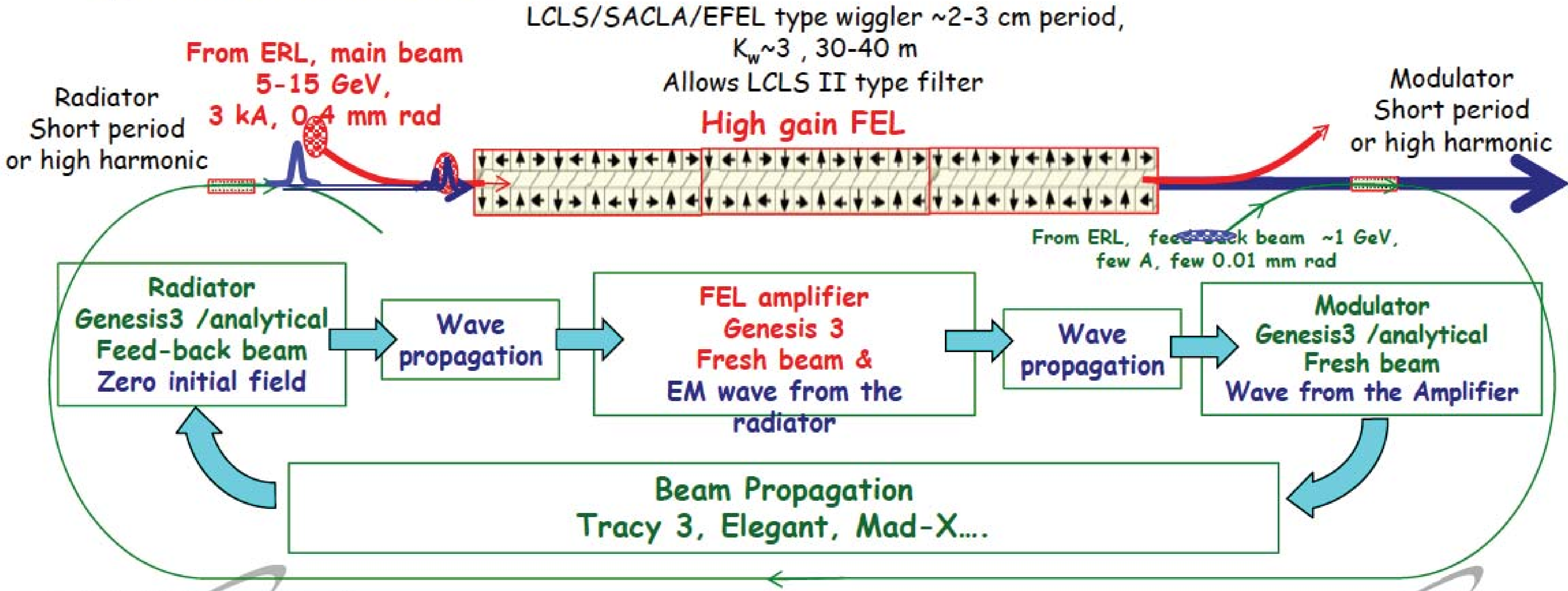


Y. Shvyd'ko et al., Nature Photonics 5, 539–542 (2011)

- **An X-ray pulse is stored in a diamond cavity→ multi-pass gain & spectral cleaning**
- **Provide transform limited BW→1�10^{-7} - 5�10^{-7} for σ_t=1-0.1ps @ λ ~1 Å**
- **Zig-zag path cavity allows wavelength tuning**
- **Originally proposed in 1984 by Collela and Luccio and resurrected in 2008 (K-J. Kim, S. Reiche, Y. Shvyd'ko, PRL 100, 244802 (2008)**

OFFELO

1. High gain amplifier/ main e-beam (from ERL or CW linac)
2. Feed-back is provided by a low-current e-beam
3. Feed-back e-beam picks the energy modulation from the FEL laser beam in modulator, preserves the correlations at 1/10th of the FEL wavelength in the long transport line, radiates coherently in the radiator.
4. The later serves as the input into the high gain FEL & compeates wit the spontaneous radiation



LCLS/SACLA/EFEL type wiggler ~2-3 cm period,
K_w~3 , 30-40 m
Allows LCLS II type filter

From ERL, main beam
5-15 GeV,
3 kA, 0.4 mm rad

Radiator
Short period
or high harmonic

High gain FEL

Modulator
Short period
or high harmonic

From ERL, feed-back beam ~1 GeV,
few A, few 0.01 mm rad

Radiator
Genesis3 /analytical
Feed-back beam
Zero initial field

Wave
propagation

FEL amplifier
Genesis 3
Fresh beam &
EM wave from the radiator

Wave
propagation

Modulator
Genesis3 /analytical
Fresh beam
Wave from the Amplifier

Beam Propagation
Tracy 3, Elegant, Mad-X….

Conclusion

Conclusion

- ERL FELs have been successfully operating/operated around the world and are routinely providing high quality electron beams for users.

- Expanding the working regime of ERL FELs to X-Rays (soft and hard) is very beneficial and there are various ongoing proposals for such effort.

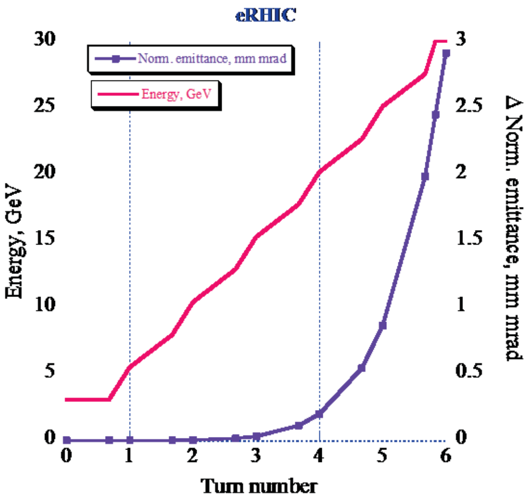
- The strong CSR effect residing in the strong bunch compressor for a X-ray ERL FEL could be alleviated/solved by using advanced compressing schemes. Such schemes have been applied to multiple cases and have proved to be successful.

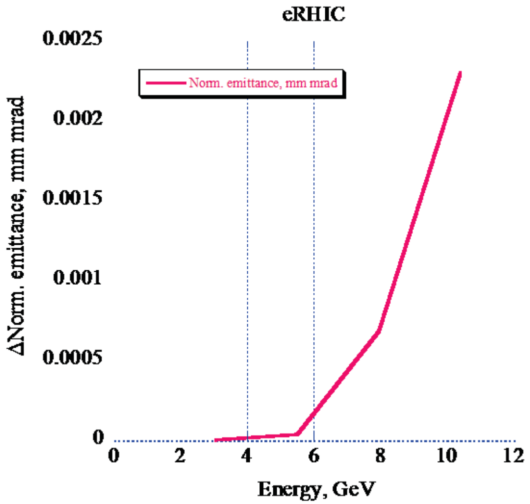
- To further improve the bandwidth of such a high-gain X-Ray ERL FEL would require some new techniques/novel ideas. Various approaches have been tested/studied for this purpose.

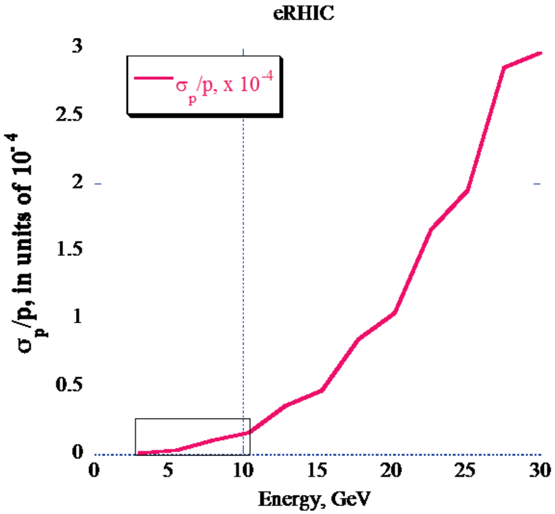
Thank you for your attention!

Backup slides

Beam parameters for eRHIC FEL



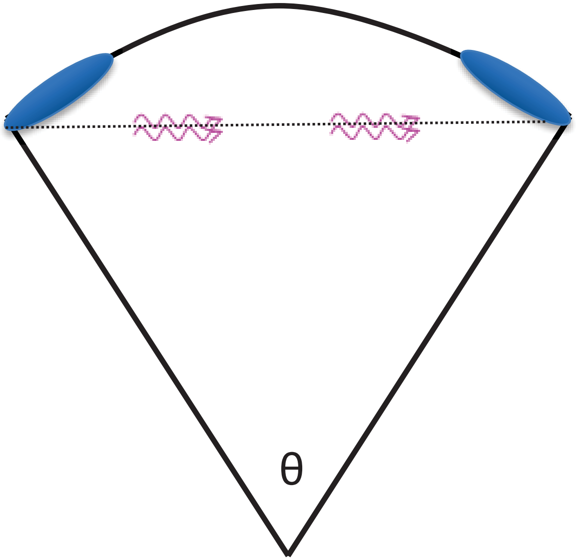




Choose low energy (~ 10 GeV) for FEL to avoid severe blow up in both emittance and energy spread caused by synchrotron radiation. Normalized emittance is largely depend on the injector.

Coherent Synchrotron radiation and its effect on beam quality

Coherent synchrotron radiation takes place in a circular orbit when the radiation from the tail of a bunch can be seen by the head, i.e. the bunch length σ_s is smaller then the slippage of radiation during the circular orbit → head gains energy while tail loses energy.



Criteria $\sigma_s < \rho\theta^3 / 24$

Energy change rate

$$\left(\frac{dE}{d(ct)}\right)_{CSR} \approx -\frac{2N_b e^2}{(2\pi)^{1/2} 3^{1/3} \rho^{2/3} \sigma_s^{4/3}} F\left(\frac{s}{\sigma_s}\right)$$

Gaussian

$$F(x) = \int_{-\infty}^{x} \frac{dx'}{(x-x')^{1/3}} \frac{\partial}{\partial x'} e^{-\frac{x'^2}{2}}$$

Overtaking potential function

$$\left(\frac{dE}{d(ct)}\right)_{CSR} \approx -\frac{2N_b e^2}{3^{1/3} \rho^{2/3} L_b s^{1/3}}$$

Uniform

Coherent Synchrotron radiation and its effect on beam quality

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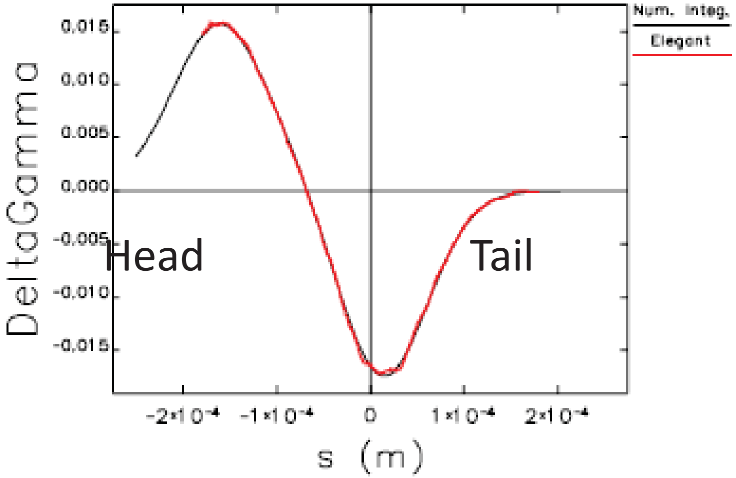

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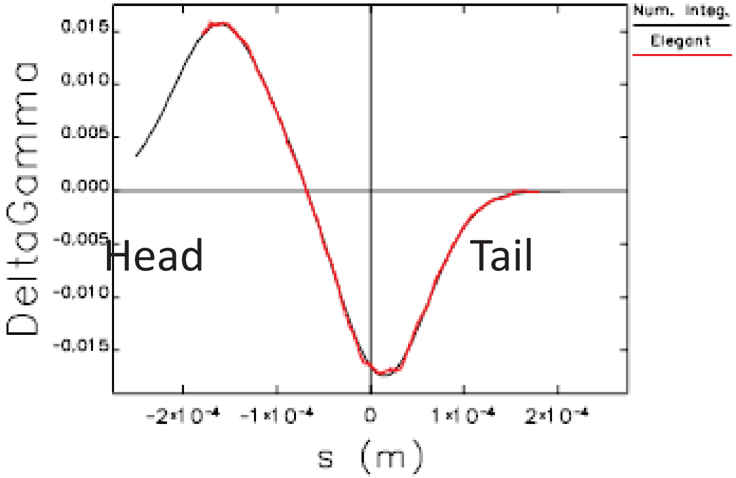

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For an achromat system

$$\left(\frac{dE}{d(ct)}\right)_{CSR} \approx -\frac{2N_b e^2}{(2\pi)^{1/2} 3^{1/3} \rho^{2/3} \sigma_s^{4/3}} F\left(\frac{s}{\sigma_s}\right)$$ Gaussian

$$F(x) = \int_{-\infty}^{x} \frac{dx'}{(x-x')^{1/3}} \frac{\partial}{\partial x'} e^{-\frac{x'^2}{2}}$$ Overtaking potential function

$$\left(\frac{dE}{d(ct)}\right)_{CSR} \approx -\frac{2N_b e^2}{3^{1/3} \rho^{2/3} L_b s^{1/3}}$$ Uniform

Coherent Synchrotron radiation and its effect on beam quality

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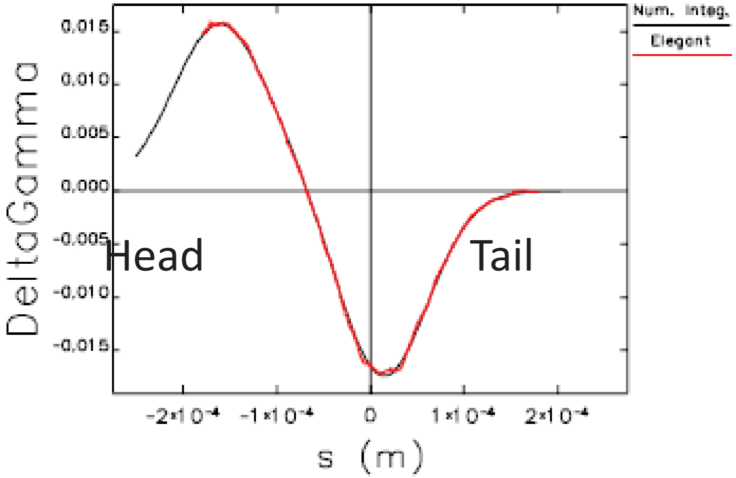

Criteria

$$\sigma_s < \rho\theta^3 / 24$$

For an achromat system

$$\delta x(s_2, z) = \frac{1}{E_0} \int_{s_1}^{s_2} \frac{d[\delta E(z, s)] R_{16}(s, s_2)}{ds} ds \neq 0;$$

$$\delta x'(s_2, z) = \frac{1}{E_0} \int_{s_1}^{s_2} \frac{d[\delta E(z, s)] R_{26}(s, s_2)}{ds} ds \neq 0.$$

Coherent Synchrotron radiation and its effect on beam quality

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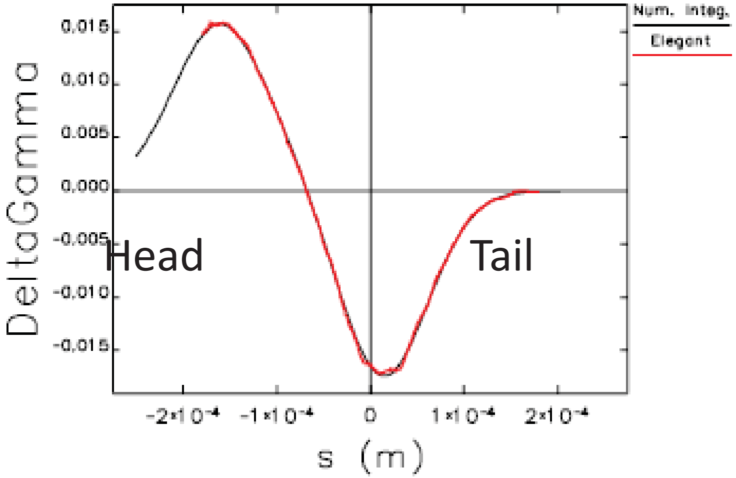

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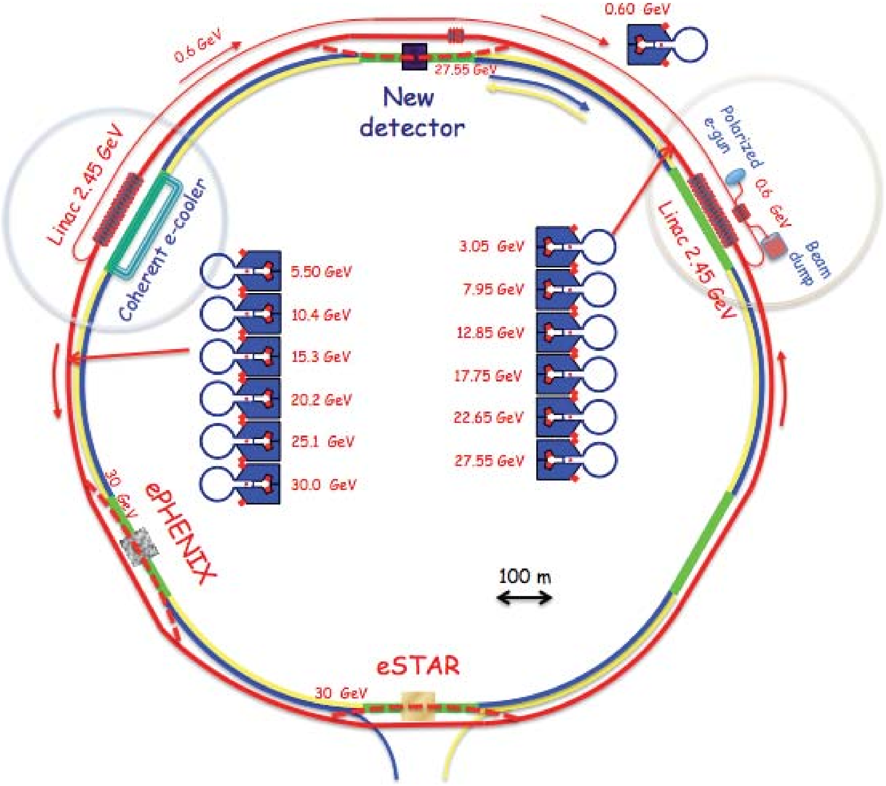
Emittance growth!!

$$\delta x'(s_2, z) = \frac{1}{E_0} \int_{s_1}^{s_2} \frac{d[\delta E(z, s)] R_{26}(s, s_2)}{ds} ds \neq 0.$$

Bunch compressor for eRHIC FEL



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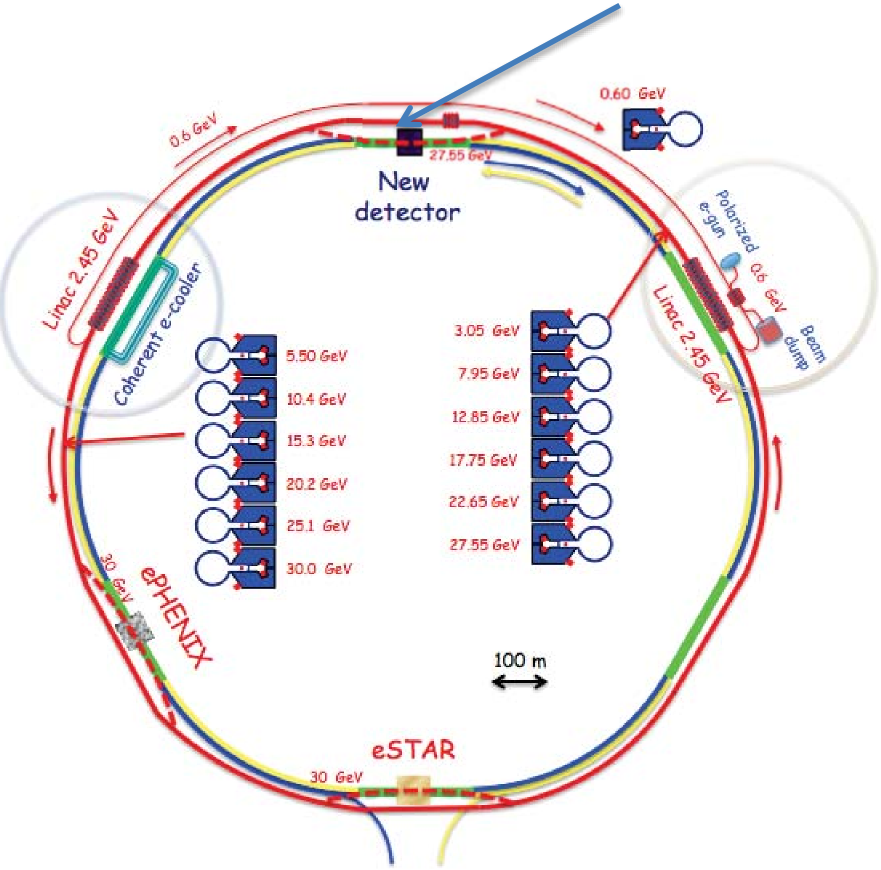

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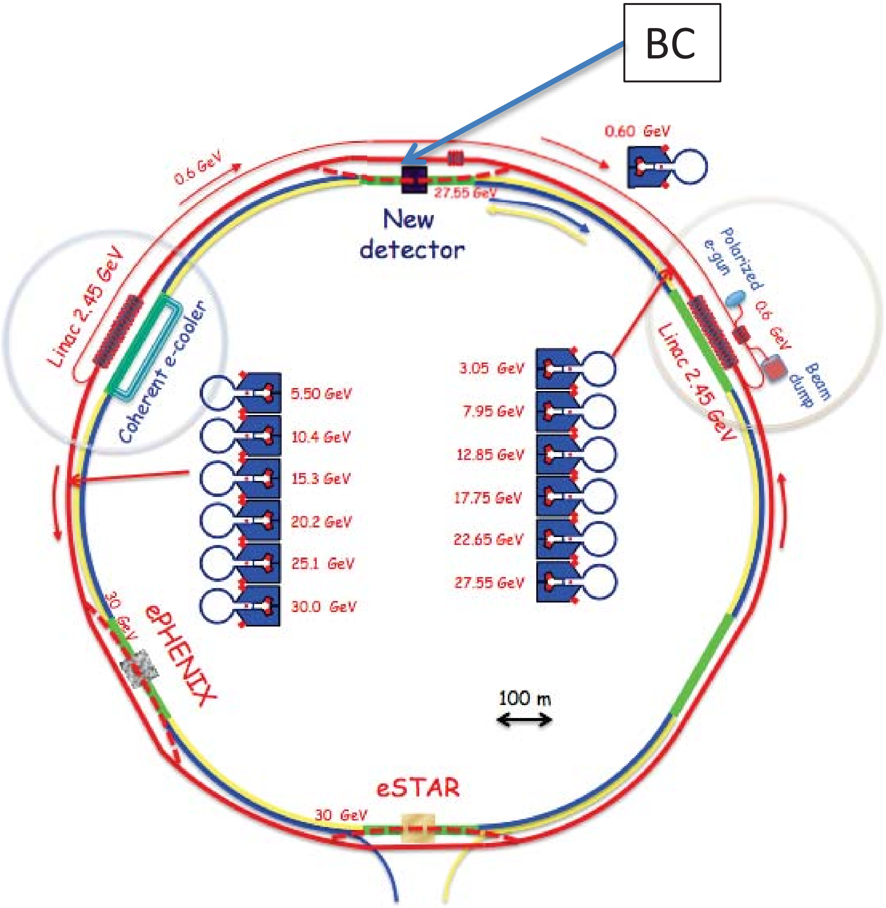
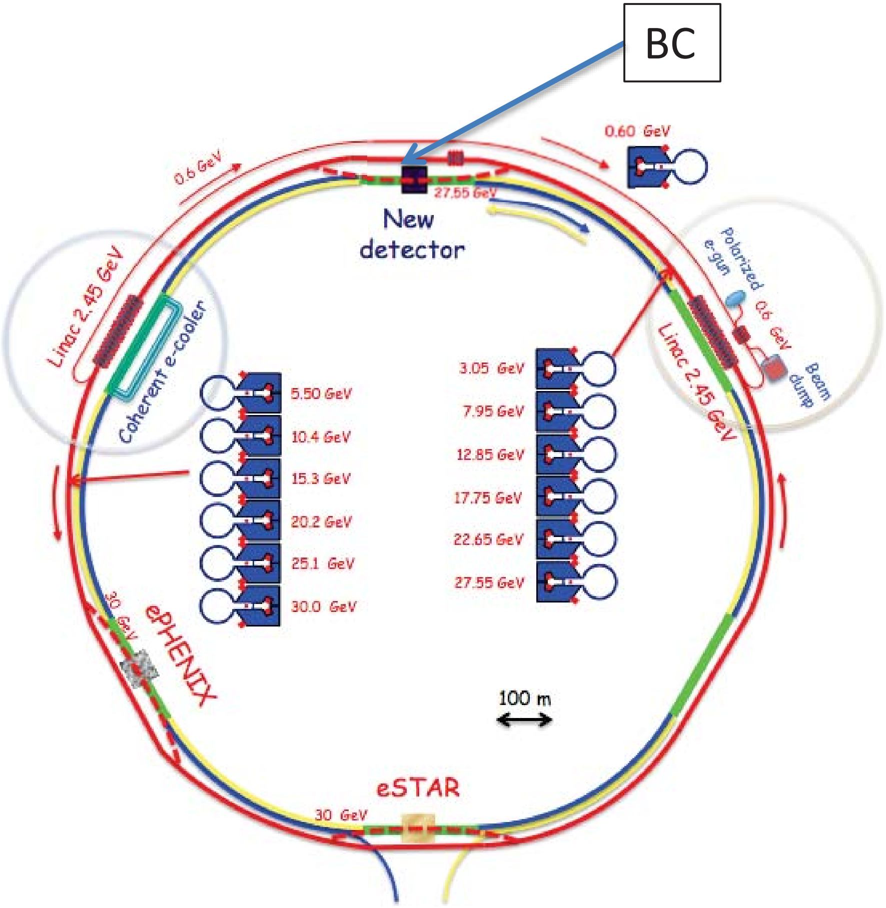


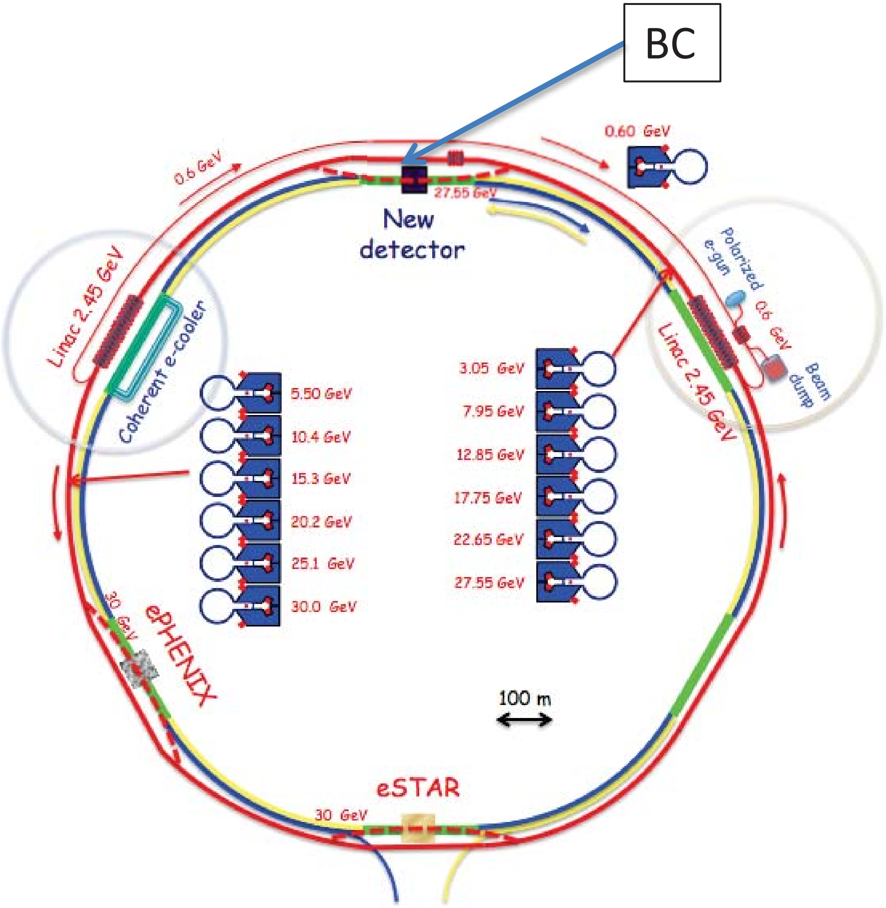
Bunch compressor for eRHIC FEL



BC

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

Bunch compressor for eRHIC FEL

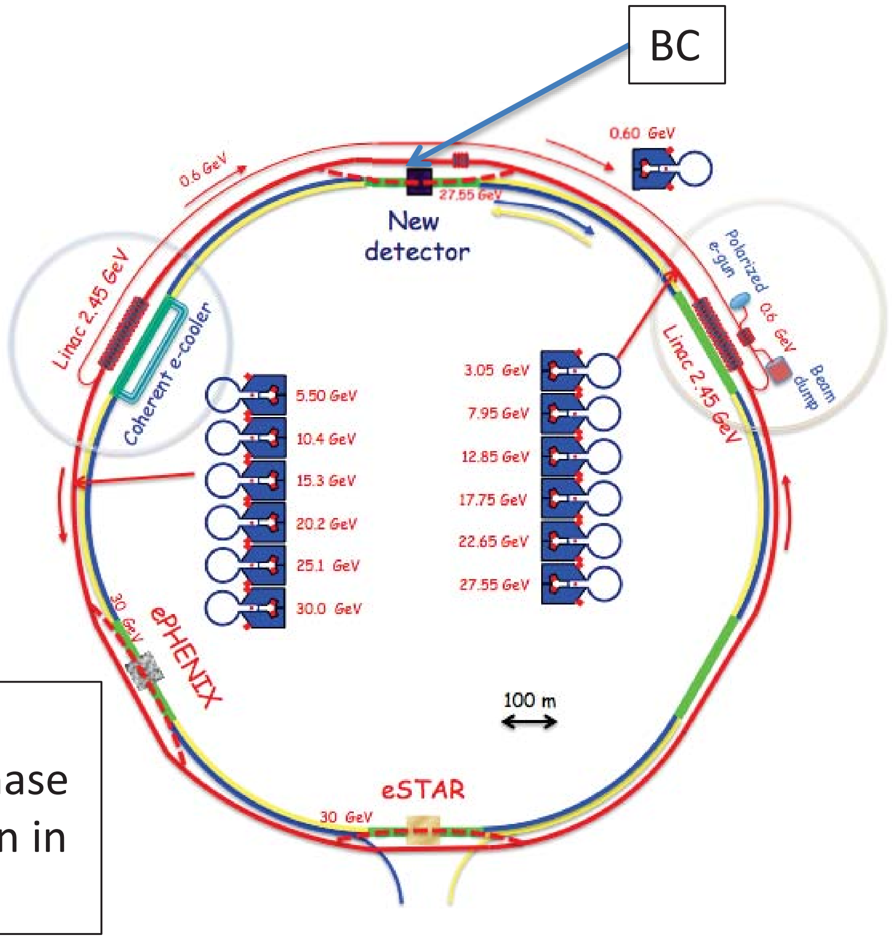


BC

Compress the 2nd pass e-beam @ 12 o’clock.

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

Bunch compressor for eRHIC FEL

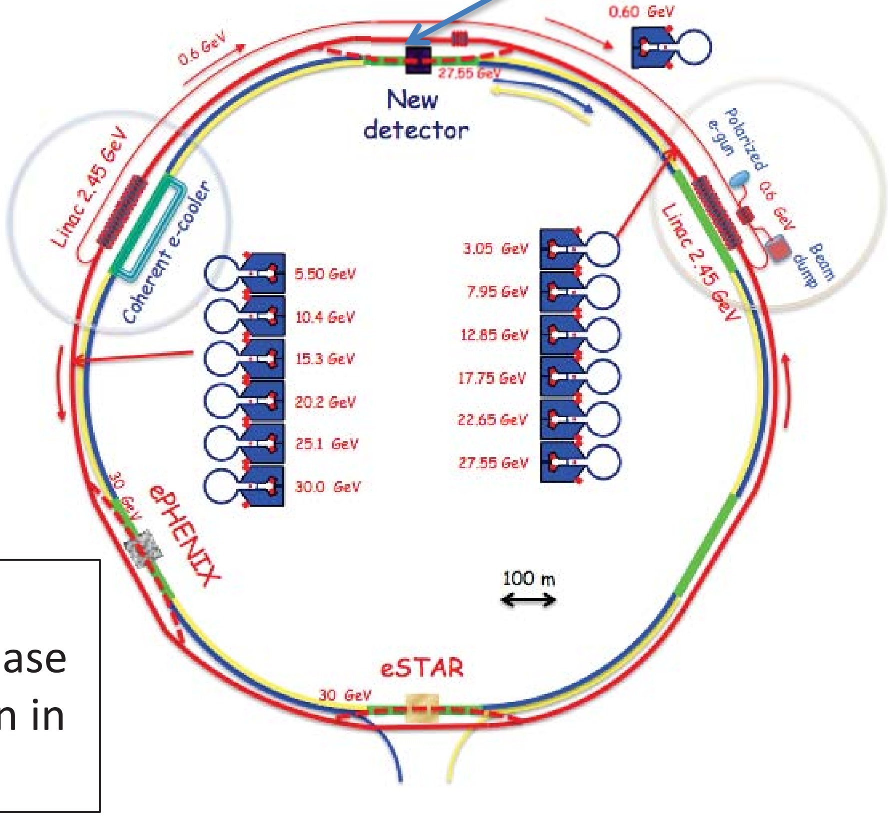


Compress the 2nd pass e-beam @ 12 o'clock.

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.

Bunch compressor for eRHIC FEL



BC

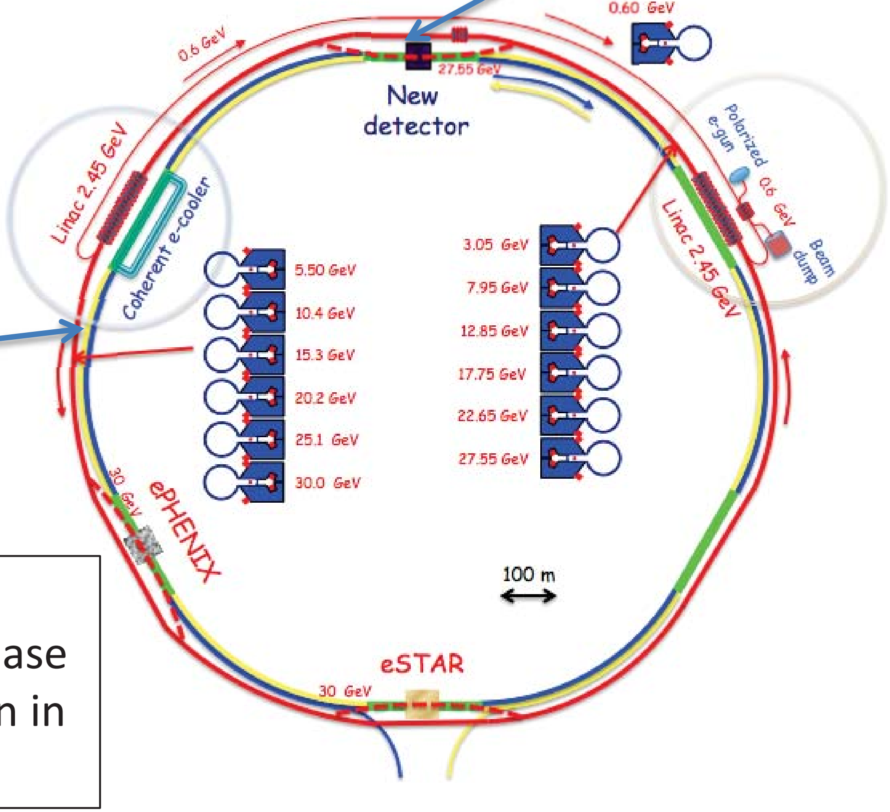
Compress the 2nd pass e-beam @ 12 o'clock.

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.

Bunch compressor for eRHIC FEL



BC

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

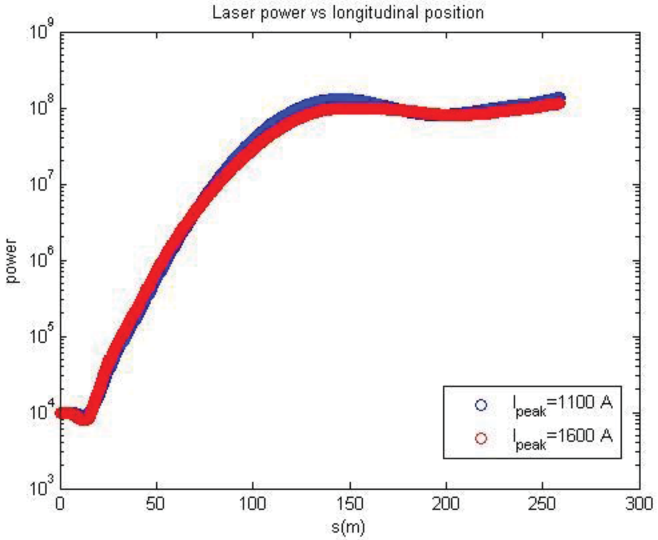
Beam extraction

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

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

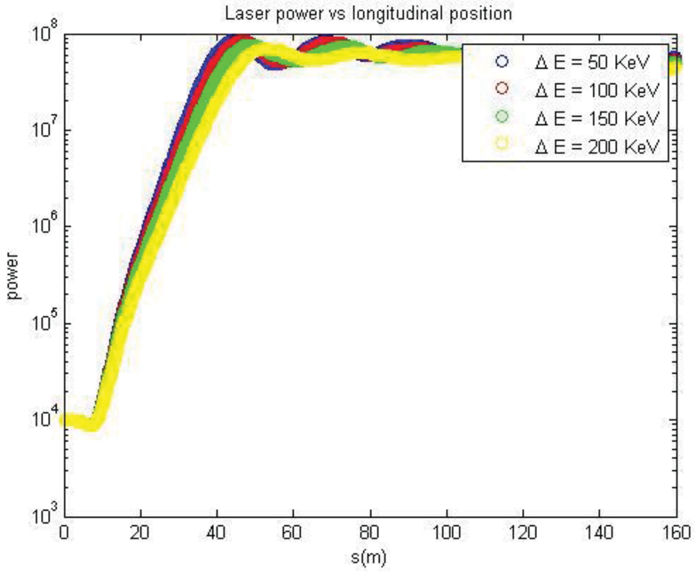
Peak current for FEL

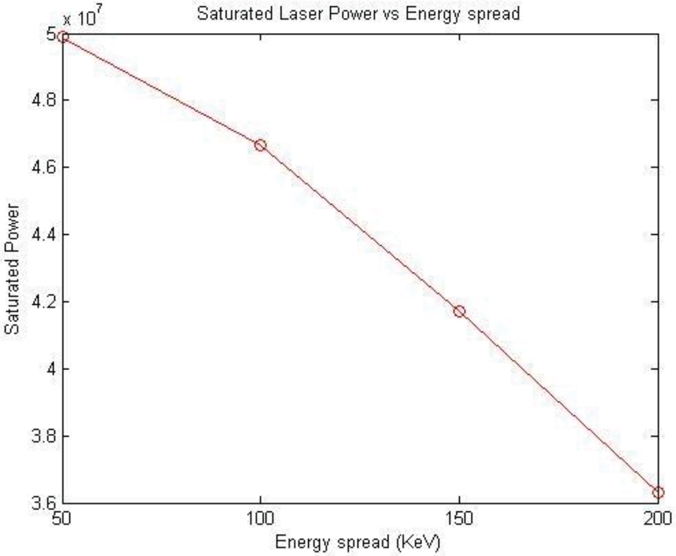
Full rotation would certainly increase the peak current. However, it would also induce a larger correlated energy spread which is hard to compensate downstream. Not to mention the magnified CSR effect. Thus a relative low (~1 kA) beam current is preferable for our implementation.



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}.





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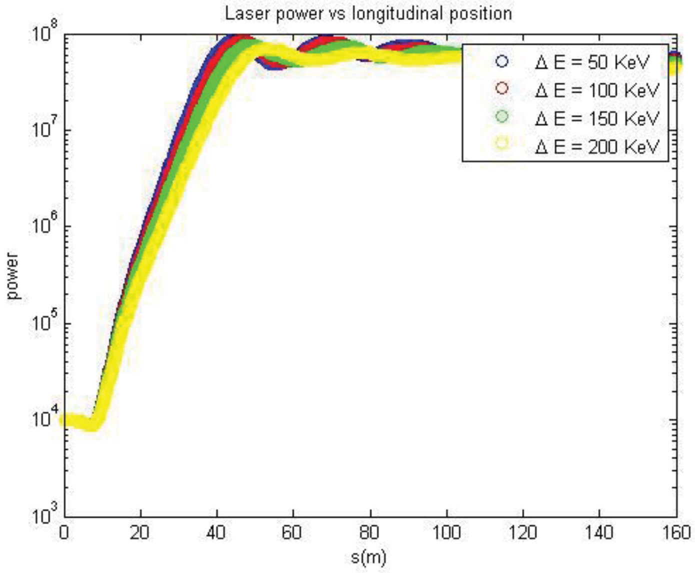
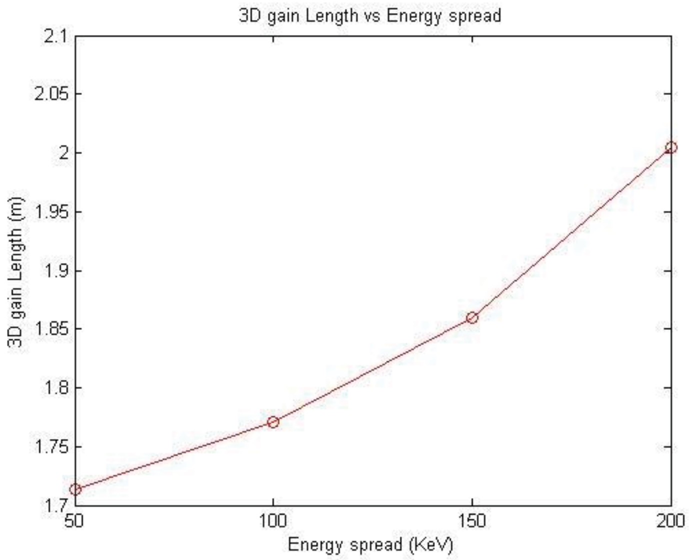
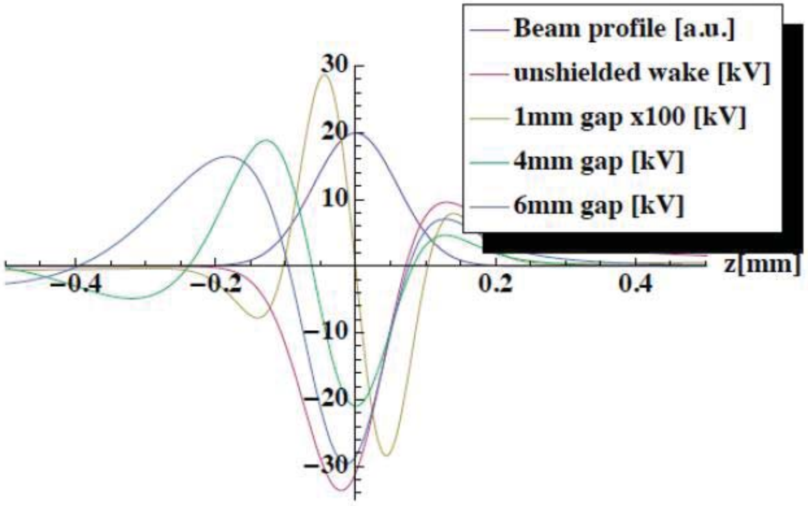


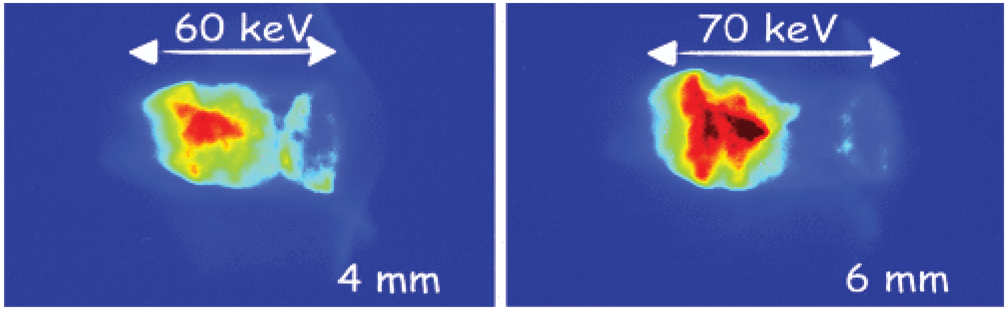


CSR shielding with parallel plates

Proximity of parallel metal plates can shield the CSR under condition

$$\left(\frac{2\pi^3}{3}\right)^{1/2}\left(\frac{\rho}{h}\right)^{3/2}\frac{\sigma_s}{\rho} > 1$$





By closing the gap, both the CSR induced energy loss and energy spread are reduced.

V. Yakimenko, M. Fedurin, V. Litvinenko, A. Fedotov, D. Kayran, and P. Muggli
Phys. Rev. Lett. **109**, 164802(2012)