Oak Ridge National Laboratory

ERL-based Compact X-Ray FEL

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Thanks to
--- ORNL : Sarah Cousineau, Vasiliy Morozov, Fulvia Pilat, Andrei Shishlo
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--- BNL : Henry Lovelace III

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Outline

- Motivation
- Concept
- Design study (so far)
  - Exploration of optics
  - Evaluation of beam parameters due to
    - Incoherent synchrotron radiation (ISR)
    - Coherent synchrotron radiation (CSR)
    - SRF/RF related BBU and HOM
- Summary

Motivation

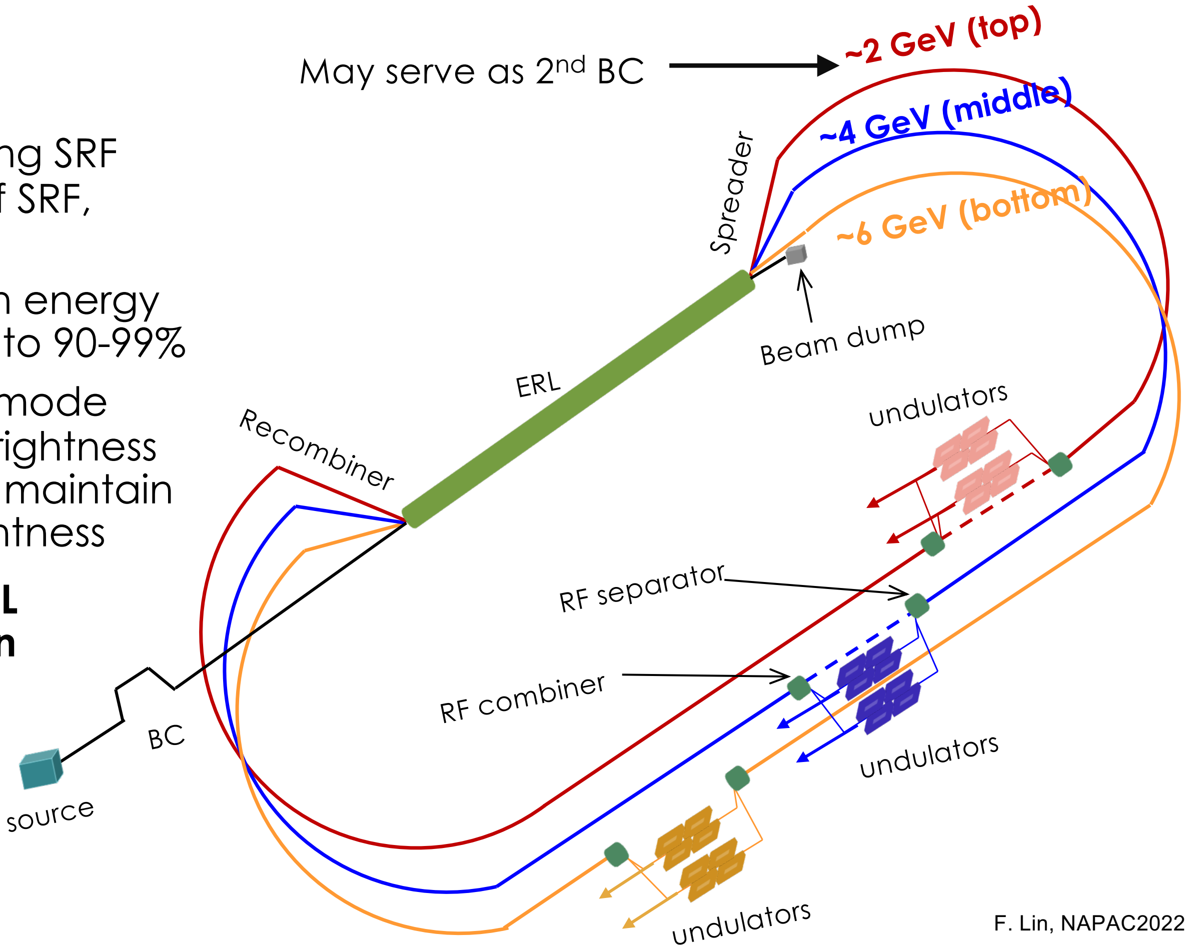
- Broad applications of XFEL
  - Exploration of matter at a length scale of the atom size (Bohr radius)
  - Exploration of dynamics of atomic and molecular process on their own time scale (Bohr time)
- Unique characteristics of XFEL
  - High peak brightness: up to $10^{34} - 10^{35}$ Photons/(s mm^{2}mrad^2 0.1% BW), Short photon wavelength: ~angstroms (1 Å -> 12.4 keV), Short pulse length: ~ femtoseconds
- Requirements on electron beams

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_u^2}{2}\right);\ E_r = h\frac{c}{\lambda_r} = \hbar\omega$$

  - Small beam emittance $\epsilon \sim pm$, small beam energy spread $\sigma_E/_E < 10^{-3}$, short bunch length $\sigma_z \sim fs - ps$, high beam energy GeV level (for high photon flux and short photon wavelength)
- All existing XFELs are driven by Linacs to preserve electron beam qualities.
  - High-gradient normal conducting RF cavities are used to control the linac length but limit the bunch rep rate, resulting in average photon brightness of as much as 10 orders of magnitude lower than the peak one
  - High-gradient SRF technology makes the CW beam operation mode possible to boost the average photon brightness

Concept of ERL-based compact XFEL

- Advantages:
  - Cost-effective: recirculating SRF cavities, operation cost of SRF, short RF section
  - Energy saving: ERL with an energy recovery efficiency of up to 90-99%
  - Better performance: CW mode enhances the average brightness significantly while can still maintain extremely high peak brightness
  - **Simultaneous multiple XFEL sources at different photon energies**



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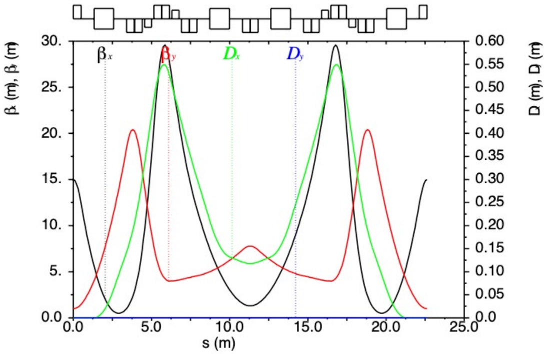
Design Goal and Approach

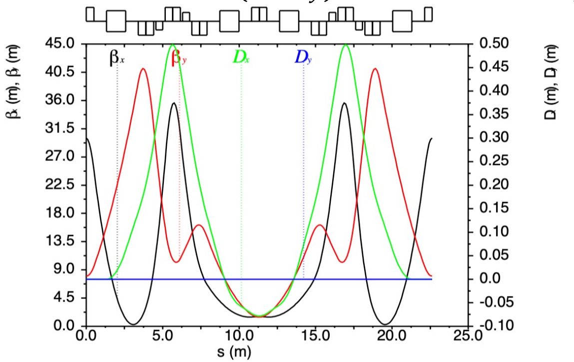
- Focus on the feasibility study of this concept
  - Design and optimization of the accelerator system
  - Explore potential R&Ds
  - Provide the XFEL performance, scale and cost of the facility
- Approaches in (some) detail
  - Several versions of preliminary designs have been explored
  - Beam energy starts from 2.25 GeV, assuming the initial beam energy is 250 MeV before the ERL and energy gain/lose is 2 GeV in the ERL
  - The ERL is treated as zero length acceleration and deceleration cavities
  - Simplify the study by applying the same arc cell optics design to all three different beam energies at 2.25, 4.25 and 6.25 GeV
  - Straights are filled with FODO cells as space holders
  - Leverage efforts on existing and developing accelerator physics and technologies, such as path length adjustment, spreader and recombiner, XFELO, injector, etc.

Arc Cell Optics for v1, v2, v3, v3.1

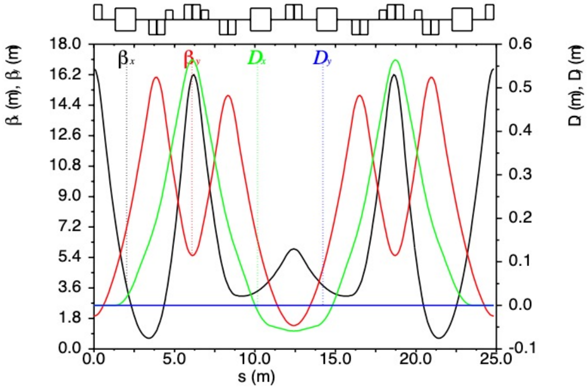
- v1: phase advances $(\phi_x, \phi_y) = (\frac{5\pi}{2}, \frac{3\pi}{2})$, $M_{56\_arc} = -28.6cm$



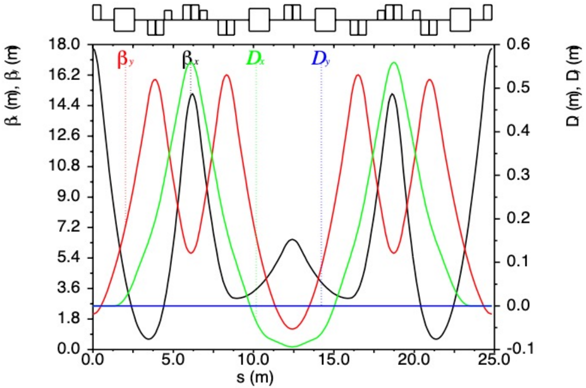
- v2: phase advances $(\phi_x, \phi_y) = (2.9\pi, 0{,}9\pi)$, $M_{56\_arc} = 0$



- v3: phase advances $(\phi_x, \phi_y) = (\frac{5\pi}{2}, \frac{3\pi}{2})$, $M_{56\_arc} = 0$



- v3.1: phase advances $(\phi_x, \phi_y) = (\frac{5\pi}{2}, \frac{3\pi}{2})$, $M_{56\_arc} = -37mm$



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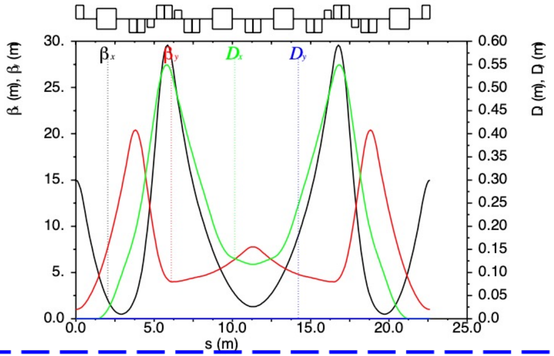

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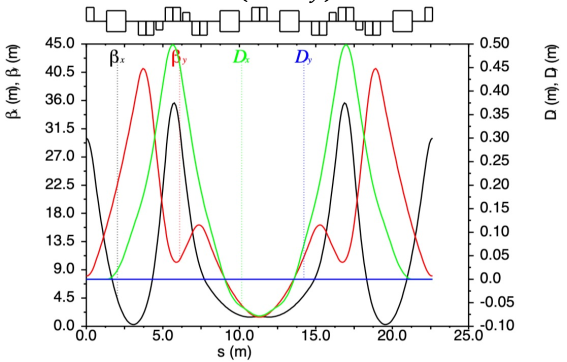

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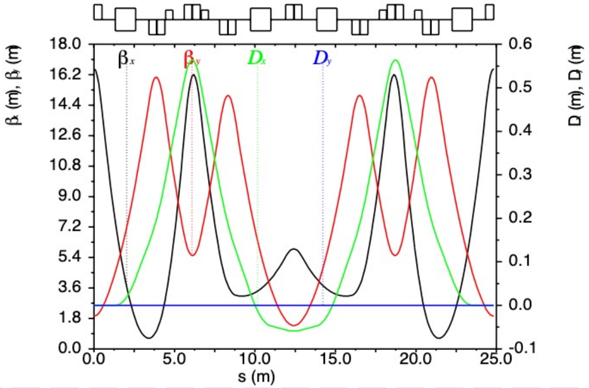

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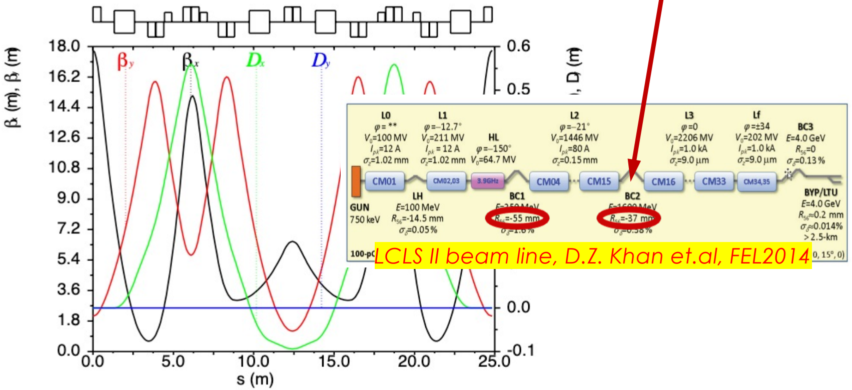

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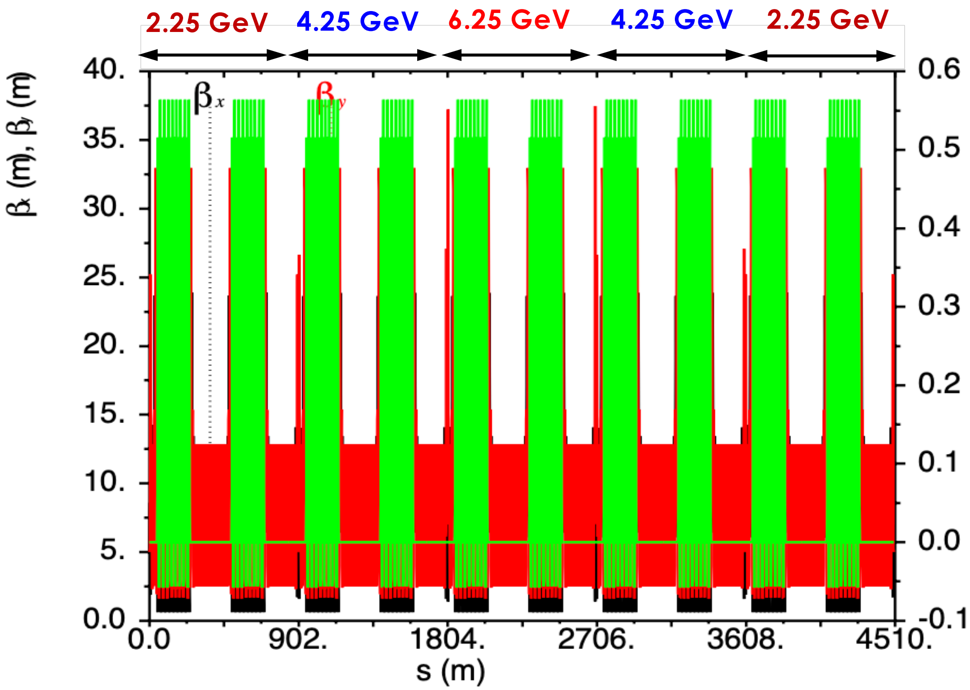
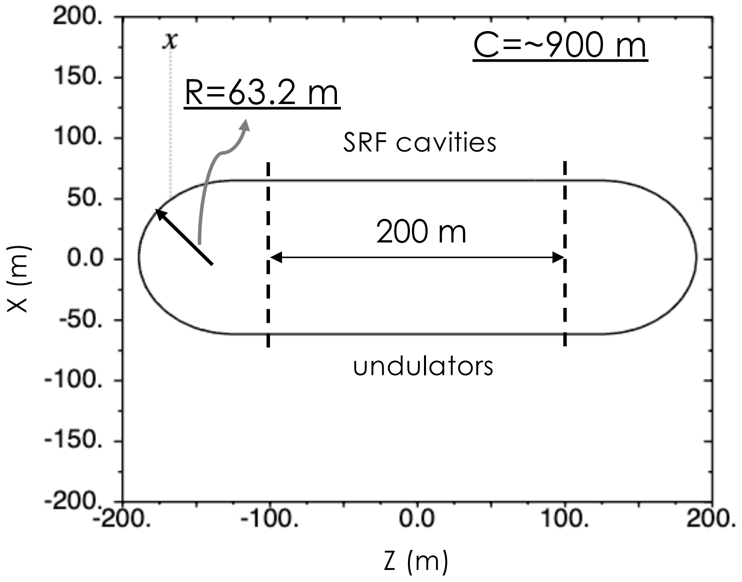
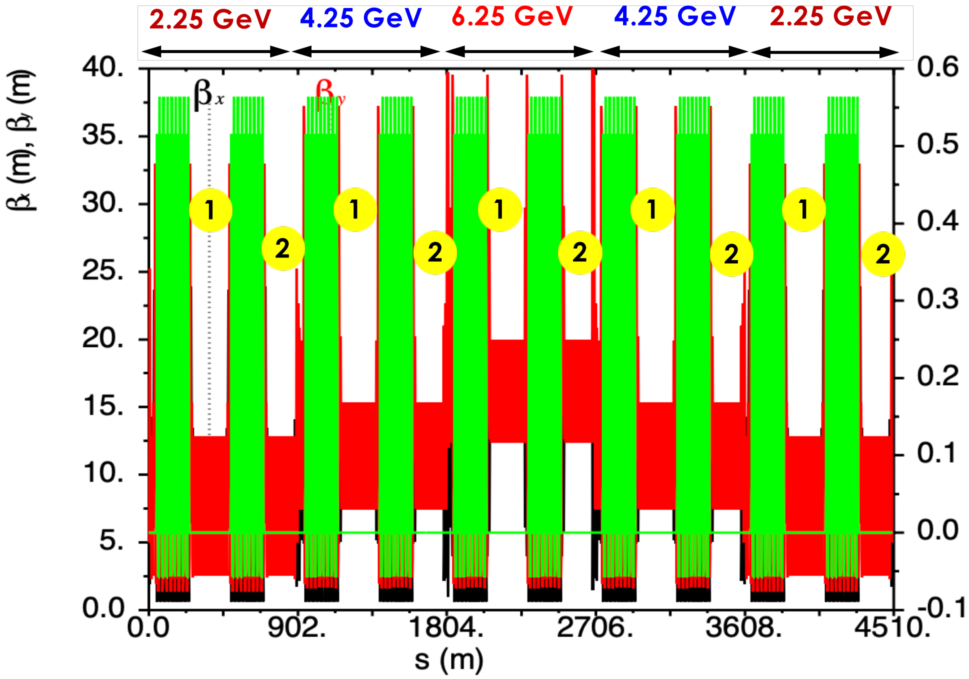
Front-to-End Optics and Geometry for v3



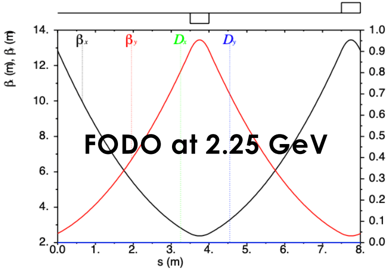


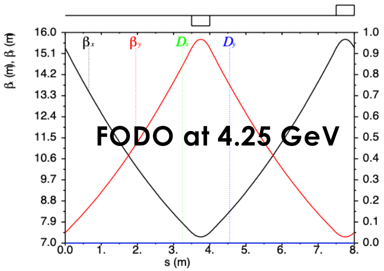
Note that, this lattice is used for the study of beam dynamics and evaluation of beam characteristics.

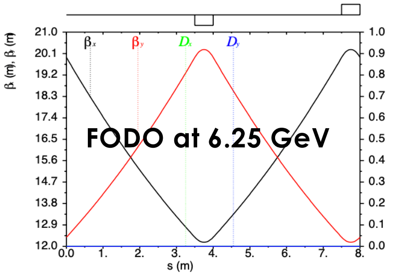
Front-to-End Optics w/ Fixed Quad Gradients in Straights



- 1 : undulator straight 2 : ERL straight
- **This is an example!** In fact, quads in the ERL straight have fixed gradients.
- Fixed quad gradients (T/m) in straights have less focusing or defocusing for beams at high energies than low energies.







High Level Beam Parameters

Energy	GeV	2.25	4.25	6.25
Circumference per energy	m	~900		
Revolution time per energy	μs	3	3	3
Average current	mA	4*	4	4
Energy loss per turn	MeV	0.18	2.26	10.56
Horizontal & vertical damping time	ms	76.1	11.3	3.6
Longitudinal damping time	ms	38.1	5.7	1.8
SR power	kW	0.7	9.1	42.2
Normalized equilibrium emittance	μm	38	254	809
Equilibrium energy spread $\frac{\delta p}{p}$	10^{-3}	0.54	1.0	1.5

* 4mA is chosen considering 1MW beam dump power with an initial injection energy of 250 MeV

Quantum Excitation from ISR

- Excitation of energy spread along the path of length *L* :

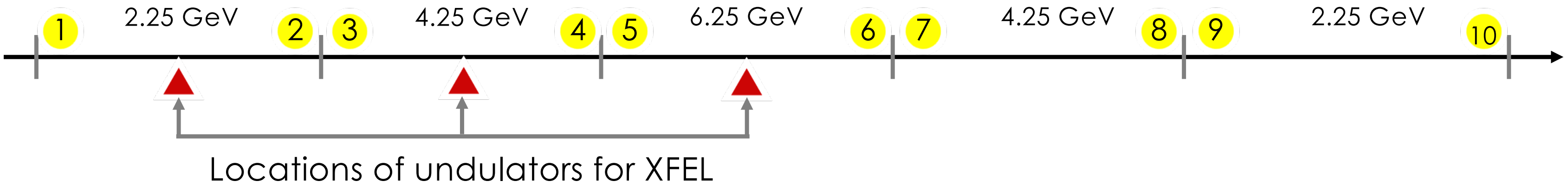
$$\Delta(\sigma_E^2) = \frac{55\alpha(\hbar c)^2}{48\sqrt{3}}\gamma^7 \int_0^L \left(\frac{1}{|\rho_x^3|} + \frac{1}{|\rho_y^3|}\right) ds \quad \Rightarrow \quad \Delta\left(\frac{\sigma_E^2}{E^2}\right) = \frac{55\alpha(\hbar c)^2}{48\sqrt{3}(mc^2)^2}\gamma^5 \int_0^L \left(\frac{1}{|\rho_x^3|} + \frac{1}{|\rho_y^3|}\right) ds$$

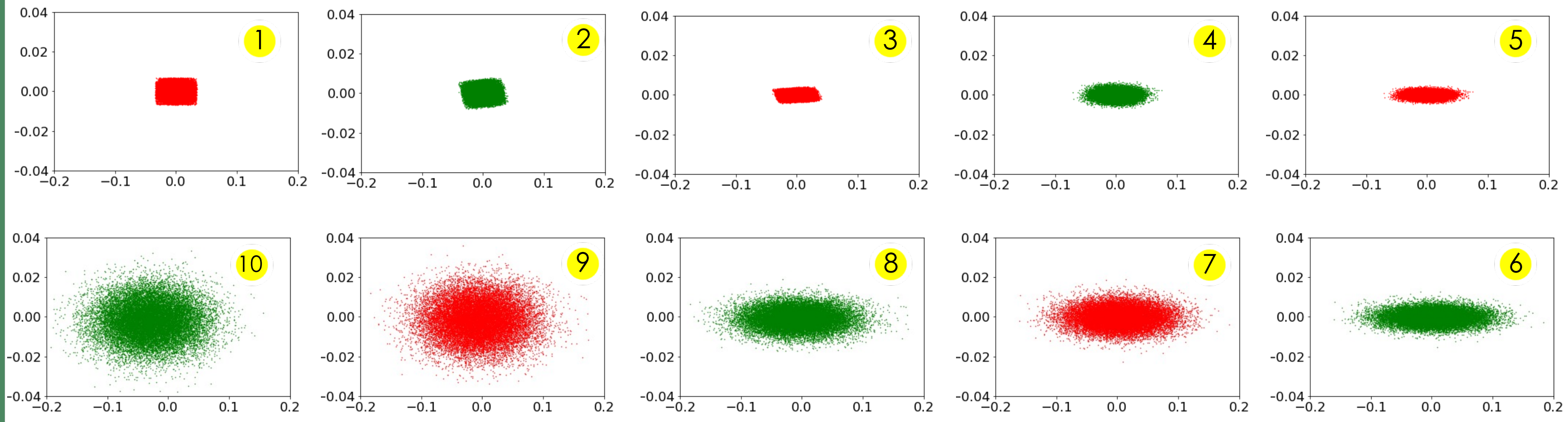
- Excitation of emittance along the path of length *L* :

$$\Delta\epsilon_u = \frac{55 r_c \hbar c}{48\sqrt{3} mc^2}\gamma^5 \int_0^L \frac{H_u}{|\rho^3|} ds \qquad here\ \ H_u = \beta_u D'^2_u + 2\alpha_u D_u D'_u + \gamma_u D_u^2$$

- Both characteristics strongly depend on the beam energy and dipole bending radius. The excitation of emittance also depends on the lattice design.

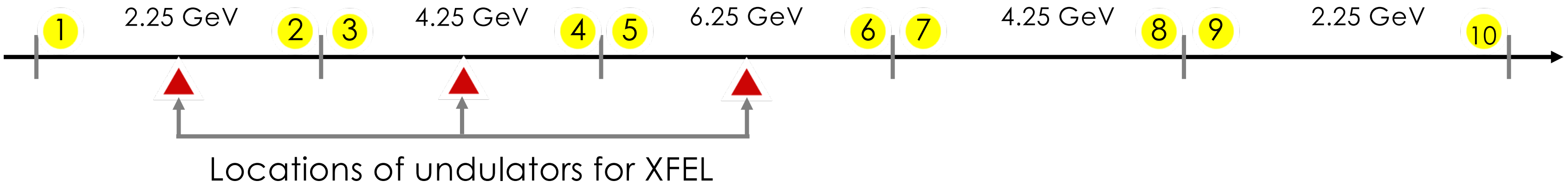
Evolution of Particle Distribution in (x, x') Phase Space

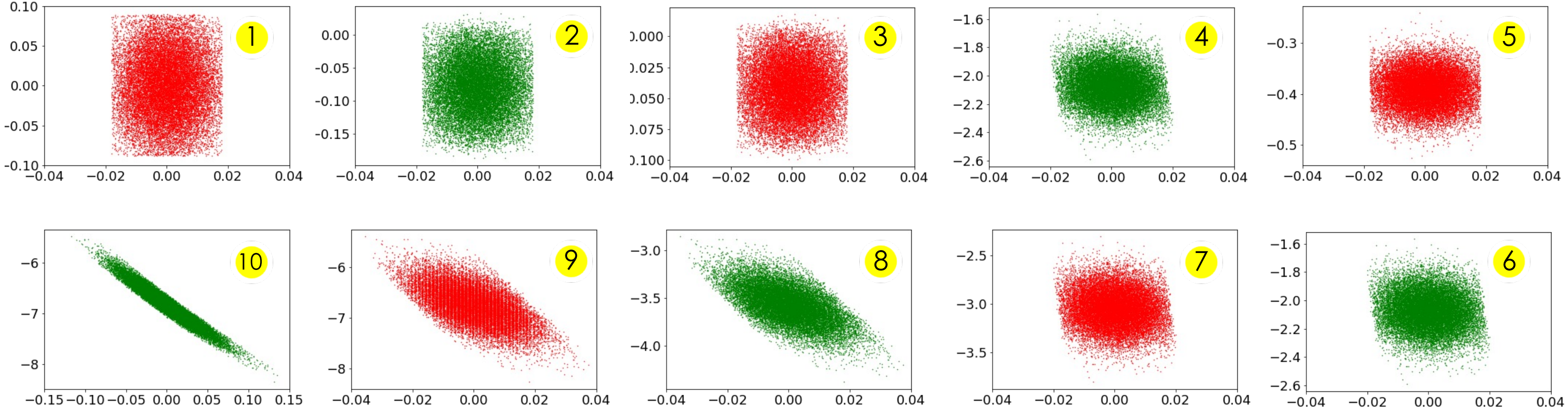




- Particles are generated with $\epsilon^{N}_{x\_ini} = 0.25\ um$
- Incoherent synchrotron radiation (ISR) on

Evolution of Particle Distribution in (z, δ) Phase Space





- Particles are generated with $\Delta E_{ini} = 0.1MeV$, rms bunch length 9um (= 30 fs)
- Incoherent synchrotron radiation (ISR) on

Evolutions of Emittance and Energy Spread

Energy		Relative energy spread (10^{-5})		UnN. Emittance (10^{-12} m)	
2.25 GeV	Initial	3.91		43.7	
	After arc 1 (undulators)	**3.97**	$\Delta\delta = 0.12$	**44.1**	$\Delta\epsilon_x = 0.7\ pm$
	After arc 2	4.03		44.4	
4.25 GeV	Before arc 3	2.13		23.5	
	After arc 3 (undulators)	**3.92**	$\Delta\delta = 2.95$	**31.4**	$\Delta\epsilon_x = 15.7\ pm$
	After arc 4	5.08		39.3	
6.25 GeV	Before arc 5	3.45		26.7	
	After arc 5 (undulators)	**9.30**	$\Delta\delta = 9.16$	**81.3**	$\Delta\epsilon_x = 108.9\ pm$
	After arc 6	12.61		135.6	
4.25 GeV	Before arc 7	18.54		199.6	
	After arc 7	18.87	$\Delta\delta = 0.61$	207.2	$\Delta\epsilon_x = 15.7\ pm$
	After arc 8	19.15		215.3	
2.25 GeV	Before arc 9	36.17		408.0	
	After arc 9	36.18	$\Delta\delta = 0.02$	409.1	$\Delta\epsilon_x = 2.4\ pm$
	After arc 10	36.19		410.4	

- $\epsilon^N_{x\_ini} = 0.25\ um$
- $\Delta E_{ini} = 0.1\ MeV$

Reduction
= 4.25 / 2.25 = 1.9

K.J Kim XFELO @ 4 GeV:
$\epsilon^N_x = 0.3\ um \Rightarrow \epsilon_x = 38.4\ pm$
$\Delta E = 0.1\ MeV \Rightarrow \frac{\Delta E}{E} = 2.5\times10^{-5}$

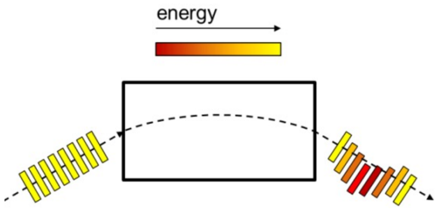
Reduction
= 6.25 / 4.25 = 1.5

Growth
= 6.25 / 4.25 = 1.5

Growth
= 4.25 / 2.25 = 1.9

CSR Introduced Emittance Growth

- Tail-head CSR interaction: radiation emitted by tailing particles in a bunch is caught by leading particles within the dipole magnet.
- This results in a slice-by-slice change of longitudinal momentum.
- This accumulates into transverse offsets and angular divergence of bunch slices, through $\Delta x \approx D_x \delta, \Delta x' \approx D_x' \delta$. These can be comparable to unperturbed rms beam size and angular divergence.



S. Di Mitri, CERN-2018-001-SP

Example

$$\Delta \varepsilon_N = \frac{(-3+2\sqrt{3})}{24\pi} \frac{\beta_x}{\gamma} \left(\frac{\Delta N_b r_e L_B}{\rho \sigma_z}\right)^2,$$

This gives 29% increase of the emittance.

Yunhai Cai, USPAS, June 2017

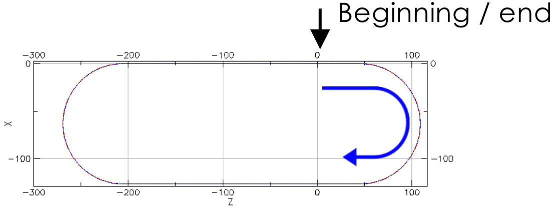
The parameters for the last bend of BC2 in LCLS

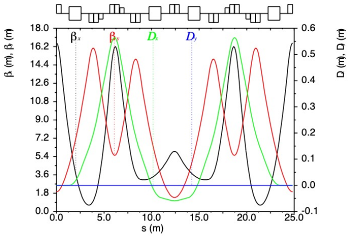
Symbol	γ	ε_N	σ_z	N_b	β_x	ρ	L_B
Value	10,000	0.5 μm	10 μm	10^9	5 m	5 m	0.5 m
2.25 GeV →	4403	0.25 um			3 m	12.8 m	1.26 m

Exploration of CSR in the Design Optics

- Three sets of electron beam parameters were explored using BMAD
  - **SASE**: based on LCLS-II design
  - **SASE-like**: like "SASE" case, but with a less CSR deterioration on the beam
  - **XFELO**: based on K.J. Kim's evaluation for CERN Accelerator School 2016
- CSR effect is explored at the minimum beam energy of 2.25 GeV

Parameter Type	Unit	SASE	SASE-like	XFELO
Energy	GeV	2.25		
Initial norm. emittance (rms)	um	0.3		
Initial energy spread (rms)	10^{-5}	4.4		
Charge per bunch	pC	30	30	100
Bunch length (rms)	um / fs	9 / 30	30 / 100	120 / 400





2 sextupole families, R_{56} = 0, T_{566}=-4.56

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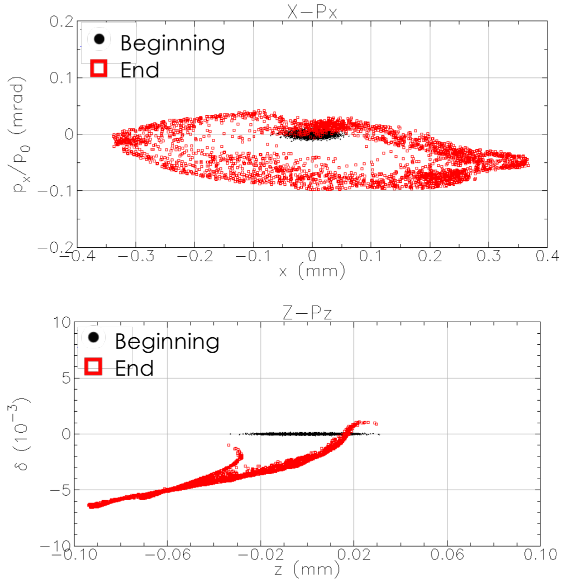
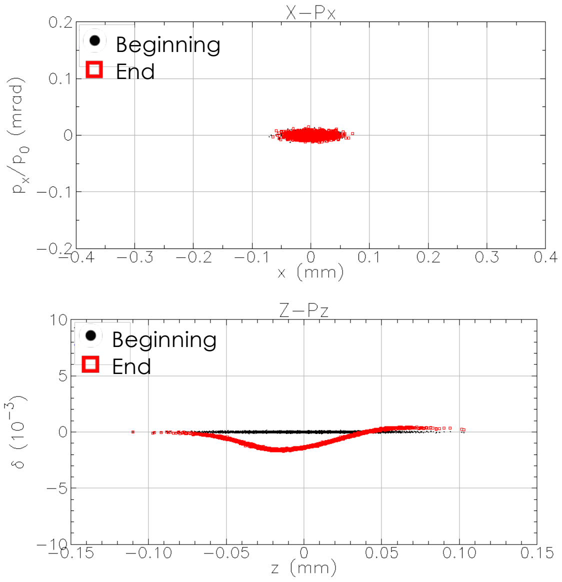
Exploration of CSR in the Design Optics (cont)

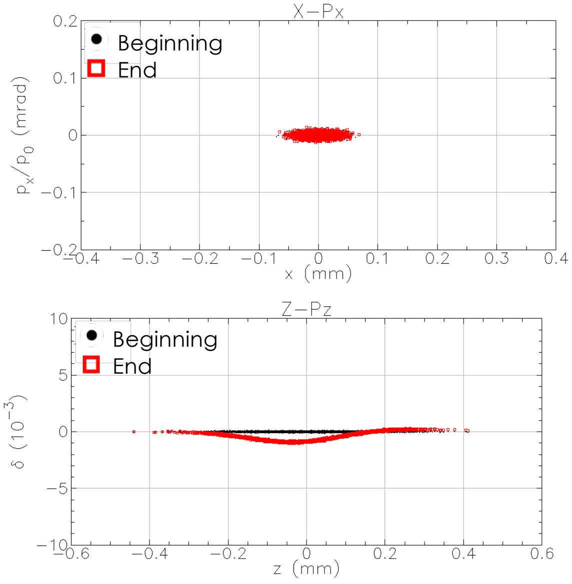
SASE parameters
30 pC, 30 fs (rms)



SASE-like parameters
30 pC, 100 fs (rms)



XFELO parameters
100 pC, 400 fs (rms)



SRF/RF Related Challenges: BBU and HOM

- Single pass beam-breakup (BBU) for SRF cavities in the injector and booster in general has much higher threshold and should not be a concern for the 4mA beam current
- One major challenge for SRF cavities in ERLs is multi-pass BBU, including transverse BBU from dipole HOM and longitudinal BBU from monopole HOM
  - Assuming similar M_{12}, $M_{3,4}$ and M_{56} in below cases and we only compare the relative impedance budgets among them.
  - Evaluation of BBU using chosen beam parameters shows a very promising result.

	Unit	6 GeV CEBAF	Jlab FEL	EIC cooler	Proposed lattice
Injected energy	MeV	67.5	9	5	250
Total beam current I_{b_t}	mA	5 x 0.2	2 x 9.1	2 x 100	6 x 4
Recirculating beam current I_{b_r}	mA	4 x 0.2	1 x 9.1	1 x 100	5 x 4
Dipole impedance budget $R_d k = -\frac{2pc}{q}\frac{1}{I_{b\_r} M \sin(\omega T_{rev})} \cong \frac{2E(eV)}{I_{b\_r} M_{12\ or\ 34}} \propto \frac{2E(eV)}{I_{b\_r}(mA)}$		168.75	1.98	0.1	25
Monopole impedance budget $R_m k = -\frac{2pc}{q}\frac{1}{I_{b\_r} M_{56} \sin(\omega T_{rev})} \cong \frac{2E(eV)}{I_{b\_r} M_{56}} \propto \frac{2E(eV)}{I_{b\_r}(mA)}$		168.75	1.98	0.1	25

* The preliminary lattice has $M_{12} \approx 5$, $M_{3,4} \approx -4$, $M_{56} \sim 0$

Summary

- Evaluation of an ERL-based X-Ray FEL is performed
  - Preliminary optics design is completed
  - Particle tracking simulation is carried out to explore the degradation of beam properties due to the both ISR and CSR
  - SRF/RF related challenges on BBU and HOM are estimated
- The results are promising
- Path Forward
  - Evaluate the XFEL performance
  - Optimize the optics to reduce the degradation of emittance and energy spread
  - Explore some details: injection/merging schemes, path length adjustment, spreader and recombiner, undulators

Thank you for your attention !

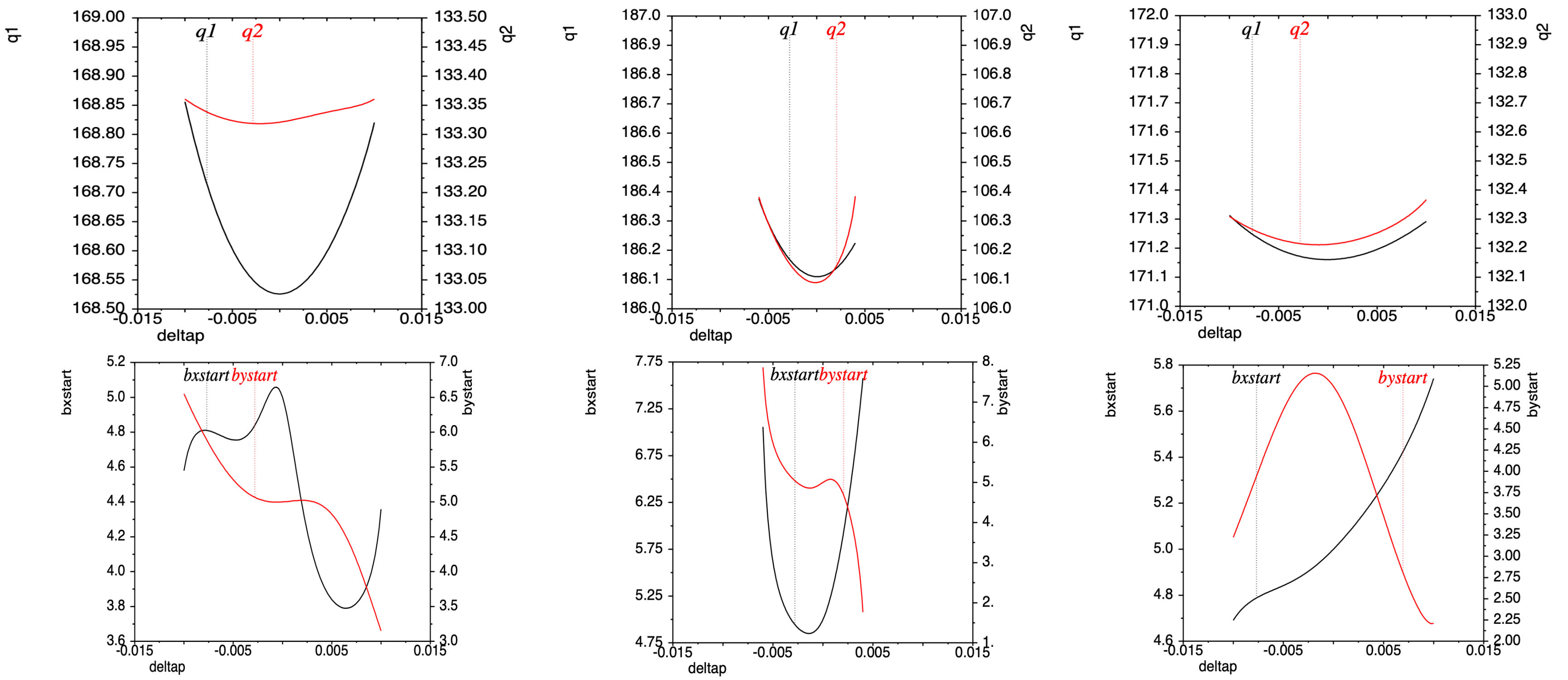
Back Up

Momentum Acceptances

v1: $(\phi_x, \phi_y) = (\frac{5\pi}{2}, \frac{3\pi}{2})$, $M_{56\_arc} = -28.6\ cm$

v2: $(\phi_x, \phi_y) = (2.9\pi, 0{,}9\pi)$, $M_{56\_arc} = 0$

v3: $(\phi_x, \phi_y) = (\frac{5\pi}{2}, \frac{3\pi}{2})$, $M_{56\_arc} = 0$



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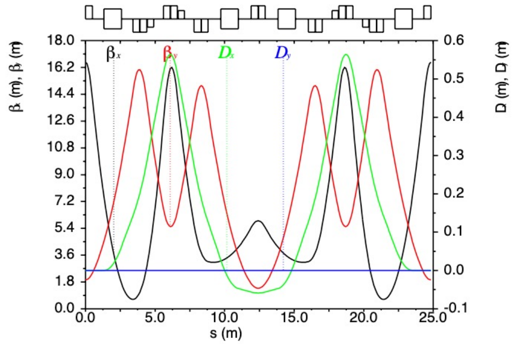
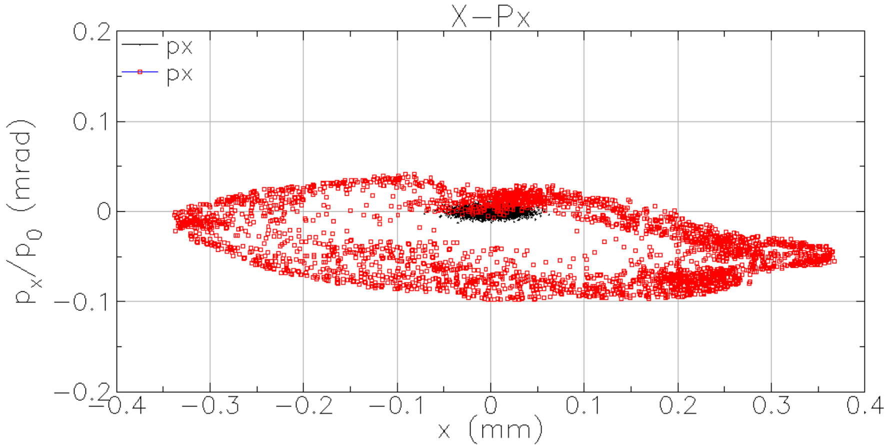
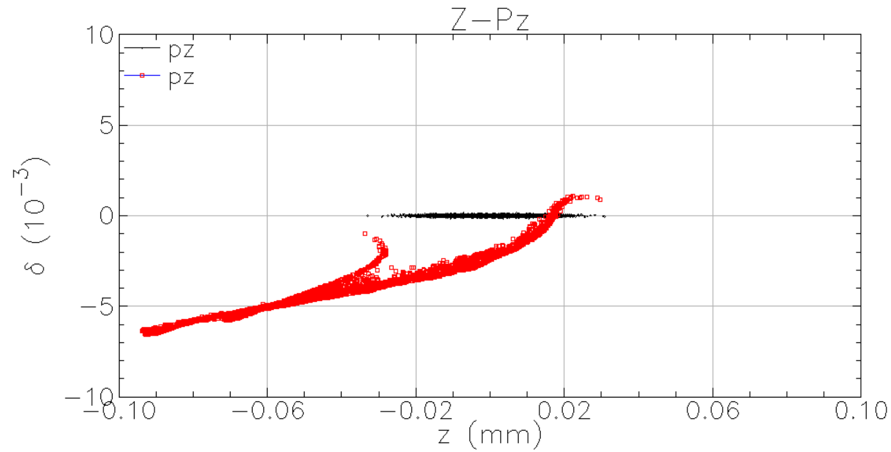
CSR Effect with SASE Parameters

- With bunch charge of 30 pC, rms bunch length of 9 um (30 fs), 2 sextupole families, R_{56} = 0, T_{566}=-4.56

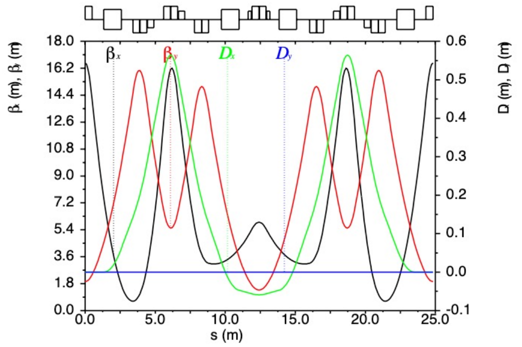


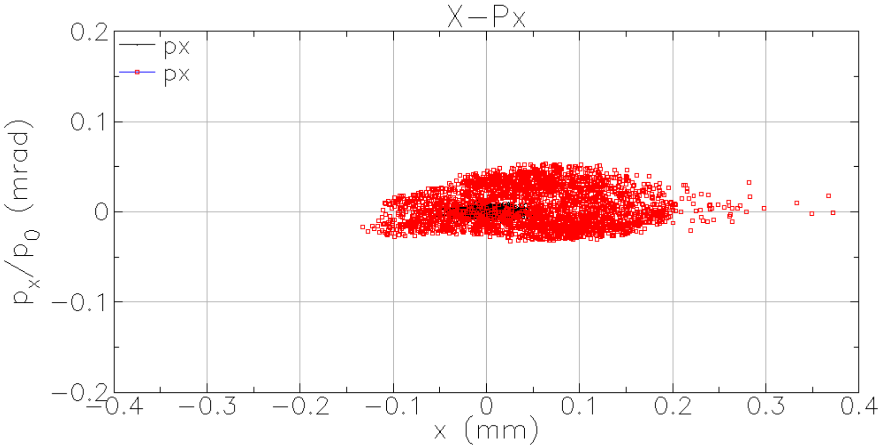


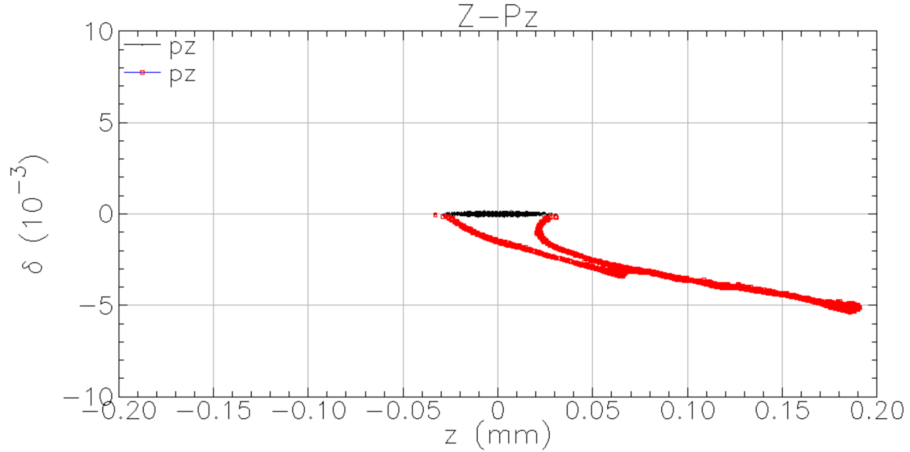


CSR Effect with SASE Parameters (Cont.)

- With bunch charge of 30 pC, rms bunch length of 9 um (30 fs), 2 sextupole families, R_{56} = 0, T_{566}=11







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Future Developments

- Increasing the longitudinal coherence of XFEL radiation
- Self-seeding
- Harmonic lasing
- Purified SASE (pSASE)
- High-brightness SASE (HB-SASE) and improved SASE (iSASE)
- EEHG
- Compact XFEL Sources based on the laser plasma accelerator (LPA) technology
- Hard X-ray FEL Oscillator (XFELO)
  - Using Bragg mirrors to form an optical cavity, may be driven by an ERL or a high-repetition rate CW superconducting linac. Studies are setup at European XFEL and LCLS-II
  - High peak brilliance, bandwidth two orders of magnitude narrower than the FEL amplifier case

R.R. Lindberg, K.-J. Kim et.al., PRST-AB 14, 010701 (2011)