Ultrashort X-ray Pulse Generation by Electron Beam Slicing in NSLS-II

Reporter: An He

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at Jlab Accelerator Division Seminar, 3/19/2015

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outline

1, Introduction

2, Theory of electron beam slicing

3, Start to end design of this system

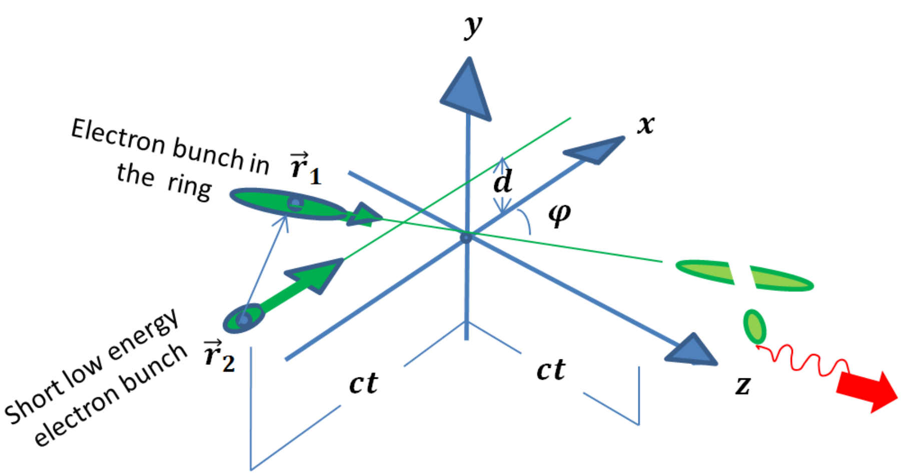
  Simulation design of low energy compressor

  Slice profile and radiation separation

  Photon flux and repetition rate

Basic idea and characteristics

	Laser slicing	Crab cavity	X-ray FEL	Ebeam slicing
Source	Storage ring	Storage ring	FEL	Storage ring
Occupied ring space	**large**	**large**	**large**	?
Pulse length	~ 100 fs	**~ ps**	< 100 fs	?
Photon flux	**~ 10^6 photons/sec/0.1%bw**	~ 10^{14} photons/sec/0.1%bw	~ 10^{12} photons/sec/0.1%bw	?
Repetition rate	1 kHz	100 MHz	**Low (120Hz for LCLS)**	?
Pulse to pulse stability	good	good	**poor**	?



Basic Idea:

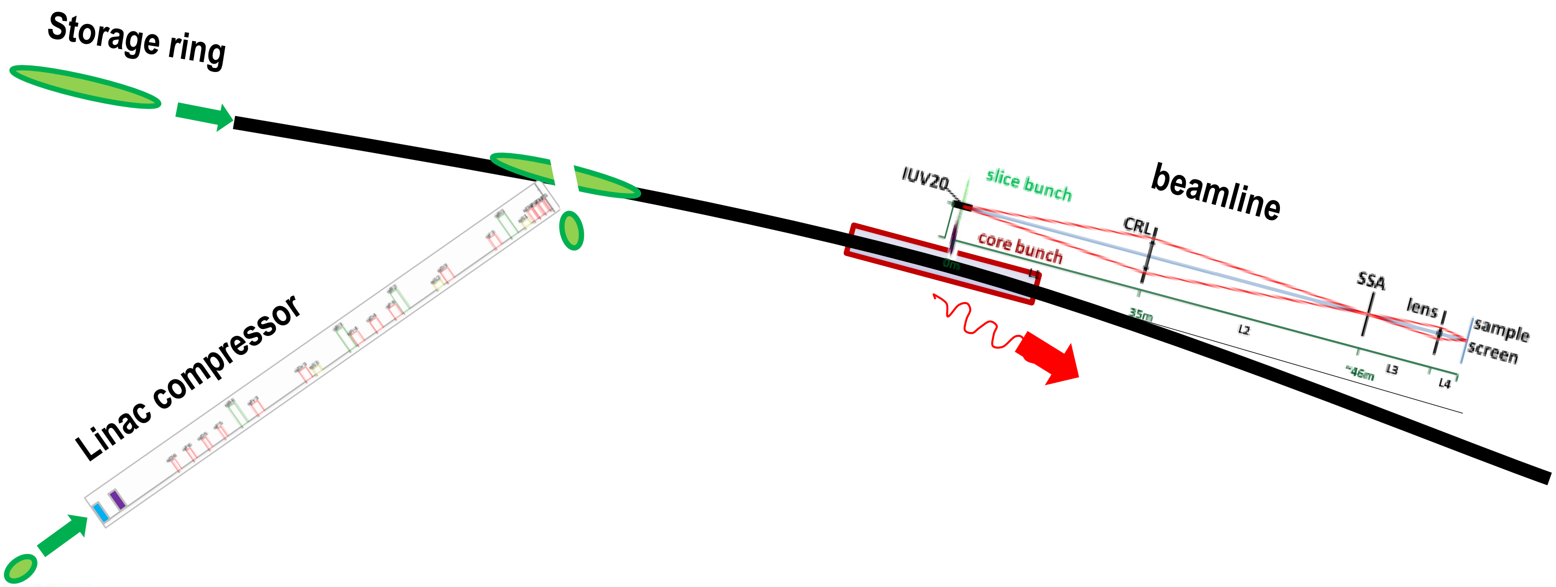
when a short electron bunch from a low energy linac passes above a storage ring bunch at a right angle, its Coulomb force will kick a short slice from the core of the storage ring bunch vertically.

The separated slice, when passing through an undulator, will radiate ultrashort x-ray pulse.

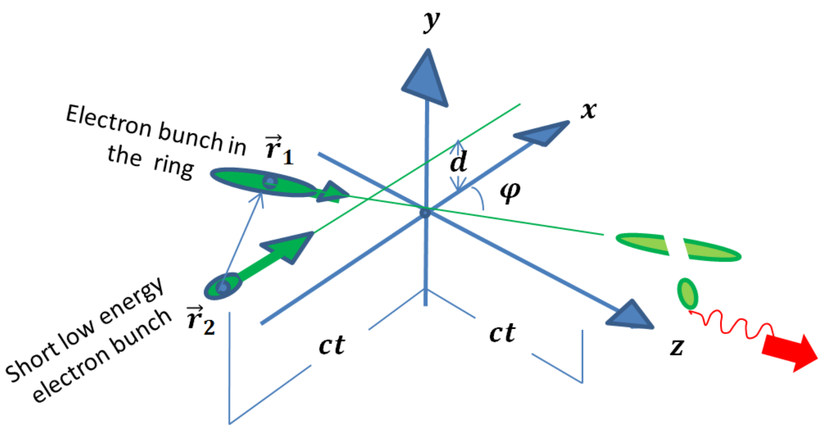
(Lihua Yu & Ferdinand Willeke)

Scheme of e-beam slicing

1. Analytical analysis of e-beam slicing (two bunches' interaction).
2. LINAC design, space charge dominated bunch compressor.
3. Choose interaction point at the storage ring.
4. Separate synchrotron radiations of the satellite from the core.
5. Photon flux and repetition rate of this e-beam slicing system.



Vertical angular kick function



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 120704 (2014)

Dependence on crossing angle of electron beam slicing in storage rings

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$$\Delta\theta_y(x_r, y_r, z_r) = \frac{eq_2 Z_0 c}{2\pi E_1} \frac{\gamma_2(1-\beta_1\beta_2\cos\varphi)}{\sqrt{\gamma_2^2(1-\cos\varphi)^2+\sin^2\varphi}} \frac{1}{\sqrt{2}\sigma_y} \times f_y(\rho, \overline{u}_1, \overline{y}_1) \Longleftarrow \text{need small } \sigma_y, \text{large } q_2$$

Nominal kick angle

Profile function gives scaled vertical kick angle and slicing length

$$f_y(\rho, \overline{u}_1, \overline{y}_1) = \int_0^\infty Re[W(\overline{u}_1 + iy)][e^{-(\rho y - \overline{y}_1)^2} - e^{-(\rho y + \overline{y}_1)^2}]dy$$

$$\rho \equiv \sqrt{\frac{\gamma_2^2}{\gamma_2^2(1-\cos\varphi)^2+\sin^2\varphi} \cdot \frac{\sigma_x^2\sin^2\varphi + \sigma_z^2(1-\cos\varphi)^2}{\sigma_y^2}} \Longleftarrow \text{need large } \rho \text{ small } \sigma_y$$

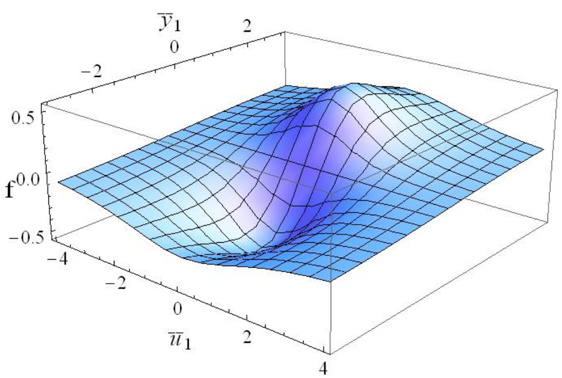
$$\overline{y}_1 \equiv \frac{d - y_r}{\sqrt{2}\sigma_y} \Longleftarrow \text{need small } d = \sqrt{2}\sigma_y$$

$$\overline{u}_1 \equiv \frac{z_r\sin\varphi + x_r(1-\cos\varphi)}{\sqrt{2\sigma_x^2\sin^2\varphi + 2\sigma_z^2(1-\cos\varphi)^2}} \Longleftarrow \text{need small } \sigma_x, \sigma_z \text{ to short pulse}$$

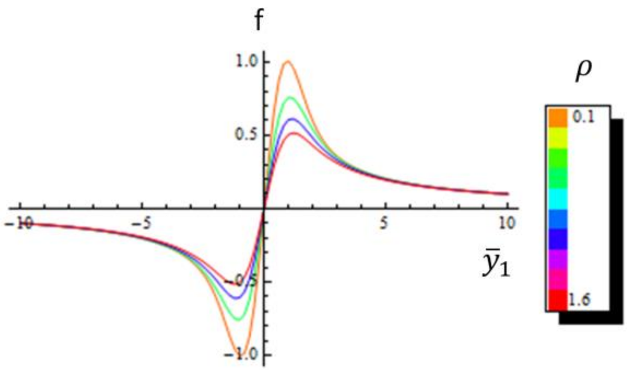
$W(u) = e^{-u^2}erfc(-iu)$, $erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^{+\infty} e^{-x^2}dx$

Kick profile and estimated slice width

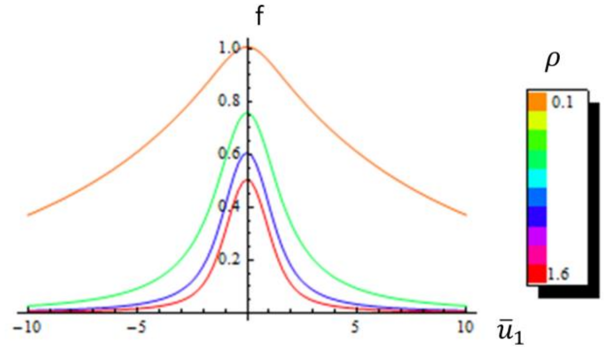
$$f(\rho,\overline{u}_1,\overline{y}_1)=\int_0^{\infty} Re[W(\overline{u}_1+iy)][e^{-(\rho y-\overline{y}_1)^2}-e^{-(\rho y+\overline{y}_1)^2}]dy$$



Profile function f at $\rho = 1.4$



Profile on axis $\bar{u}_1 = 0$
maximum f locates at $\bar{y}_1 = 1, \bar{u}_1 = 0$



Profile on axis $\bar{y}_1 = 1$

$$z_r = \bar{u}_1\sqrt{2\sigma_x^2 + 2\sigma_z^2\left(\frac{1-\cos\varphi}{\sin\varphi}\right)^2} + \left(\frac{\cos\varphi - 1}{\sin\varphi}\right)x_r.$$

Estimated result →

RMS value of satellite x-ray width
190 fs at 90° crossing angle
150 fs at 45° crossing angle

Estimated kick angle for NSLS-II

$$\Delta\theta_y(\varphi = 90^\circ) = \frac{eq_2 Z_0 c}{2\pi E_1} \frac{\gamma_2}{\sqrt{\gamma_2^2+1}} \frac{1}{\sqrt{2}\sigma_y} f(\rho, \overline{u}_1, \overline{y}_1)$$

****

NSLS-II bunch $\beta_x = 3.8$ m, $\beta_y = 25$ m ,$\varepsilon_y = 10$ pm, $\sigma_y' = 0.6$ μrad, $E_1 = 3$ GeV
linac bunch $E_2 = 20$ MeV, $q_2 = 200$ pC, $\sigma_z = \sigma_y = \sigma_x = 35$ μm
nominal kick angle

$$\Delta\theta_{y,0} = \frac{eq_2 Z_0 c}{2\pi E_1} \frac{\gamma_2}{\sqrt{\gamma_2^2+1}} \frac{1}{\sqrt{2}\sigma_y} = 24\ \mu\text{rad}$$

profile function (assume $d = \sqrt{2}\sigma_y = 50$ μm, $x_r = y_r = z_r = 0$)

$$f_{\max}(\rho = 1.4, \bar{y}_1 = 1, \bar{u}_1 = 0) = 0.54$$

kick angle

$$\Delta\theta_y = \Delta\theta_{y,0} \times f_{\max} = 24\ \mu\text{rad} \times 0.54 = 13\ \mu\text{rad}$$

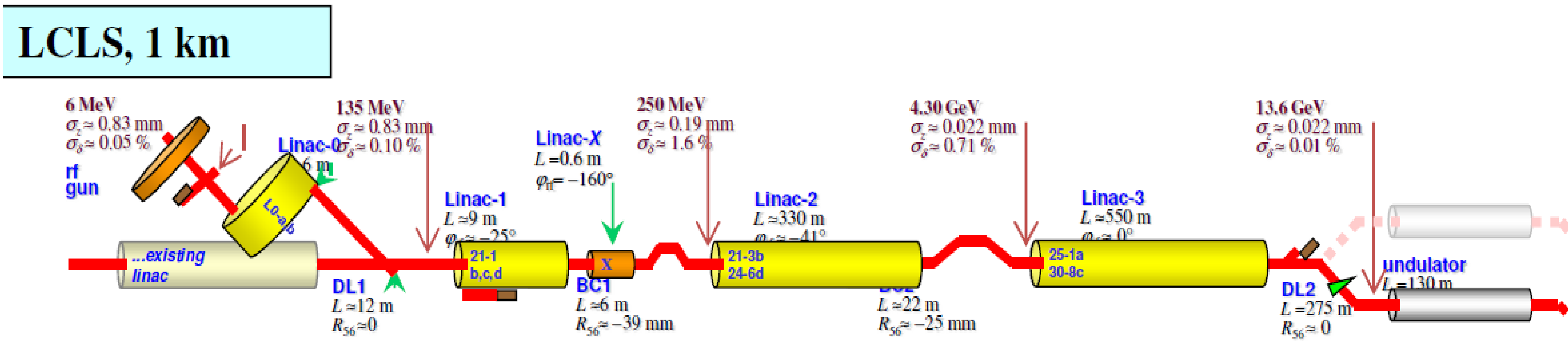
much larger than required $5\sigma_y' = 3$ μrad

We need short and small (high current), low energy bunch with high charge

$\sigma_x = \sigma_y = \sigma_z = 35$ μm
E_2=5 MeV, q_2=50 pC $\Longrightarrow \Delta\theta_y$=3.2 μrad, x-ray 150 fs
E_2=20 MeV, q_2=200 pC $\Longrightarrow \Delta\theta_y$=13 μrad, x-ray 150 fs

Conventional bunch compressor

- Difficulty:
  Space charge effects are very strong for low energy, high charge bunch.
- Conventional solution:
  first accelerate bunch to high energy, **then compress**



Picture from S. Di Mitri's lecture of linac design for FEL

- **But, we need a low cost (low energy) LINAC compressor**

Unconventional low energy bunch compressor

- Try to compress bunch **without acceleration or with a short accelerating structure** after RF-gun
- Work at **low energy (5 MeV~22MeV), space charge dominated regime**

- Bunch with **negative energy chirp** (head particle with higher energy)
- Compression section with **positive R_{56}**

- designed two compressors (length<10m):

Gun	Optimized performances	Code	Optimizer
BNL RF gun (1~10 Hz)	**~ 5 MeV, 50 pC, 166fs, 31um, 28um** (1.27ps, 2mm, 2mm at cathode)	OptiM, ELEGANT, PARMELA	Genetic algorithm
LBNL VHF gun (at 186 MHz)	**~ 22 MeV, 200 pC, 128 fs, 42 um, 25 um** (8ps, 1.5mm, 1.5mm at cathode)	IMPACT-T, IMPACT-Z	Genetic algorithm

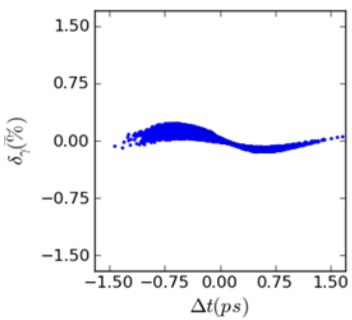
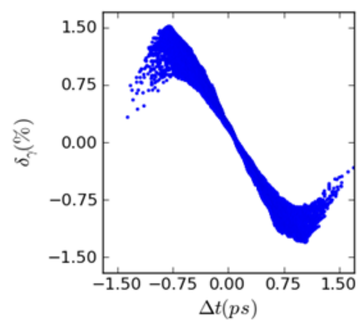
Using focus to increase energy chirp

Chicane requirement 1: $\sigma_1 \approx \sqrt{(1+hR_{56})^2\sigma_0^2 + R_{56}^2\sigma_\delta^2}$

$R_{56} = R_{56,\mathrm{chicane}} + R_{56,\mathrm{drift\ space}}$

$R_{56,\mathrm{drift\ space}} = -s/\gamma^2$

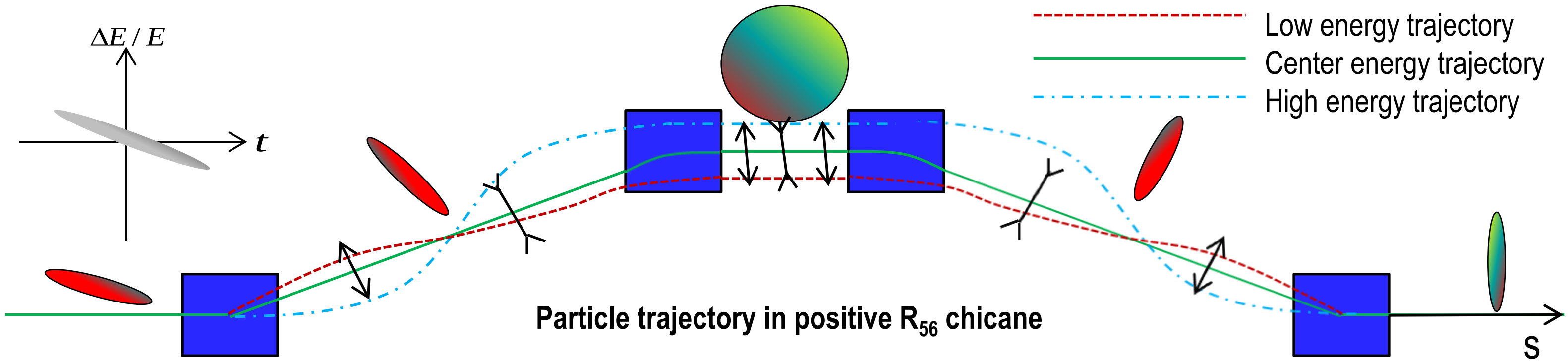
$$R_{56} = -1/h$$

Chirp at cathode -0.25%/ps (1/h=-120mm)	Chirp after focusing: -1.5%/ps (1/h=-20mm)
$R_{56,\mathrm{chicane}}$=170mm	**$R_{56,\ \mathrm{chicane}}$ = 70mm**
Large R_{56} -> longer compressed bunch length	Small R_{56} -> shorter compressed bunch length
 small negative chirp at the downstream of BNL RF-gun	 large negative chirp just at the upstream of chicane

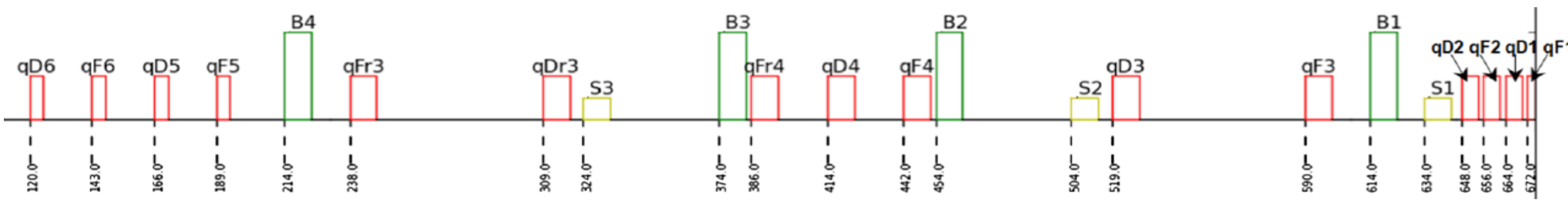
Chicane requirement 2: (100fs final bunch length as a target)
beta functions < 10m, dispersion function < 12cm, $R_{56,\ \mathrm{chicane}}$ < 84mm
| energy chirp | >1% / ps

- **Space charge effects generate negative chirp**---head particles has higher energy than tail's
- **Focus the beam to increase space charge effects, then to increase the chirp**

Positive R_{56} chicane



Particle trajectory in positive R_{56} chicane

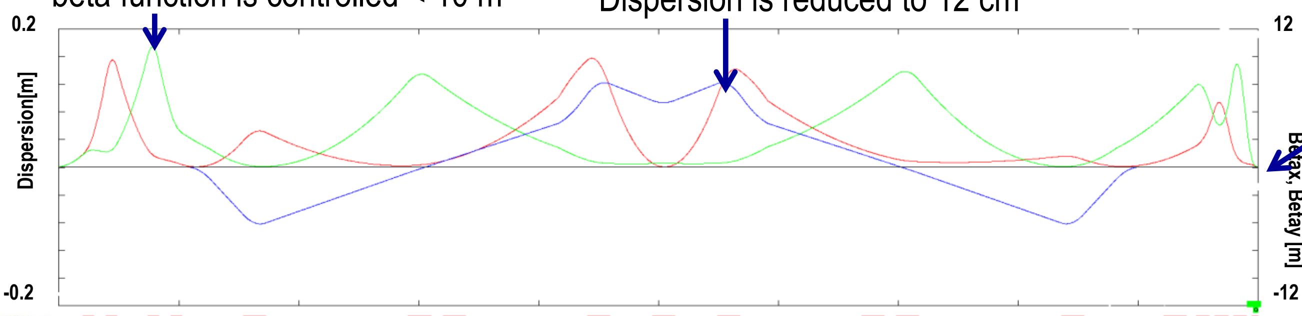


The lattice of the compressor

- **Linear design result without space charge effects (OptiM, ELEGANT) ->100 fs, 30 μm**

beta function is controlled < 10 m

Dispersion is reduced to 12 cm



100 fs at focal point without space charge

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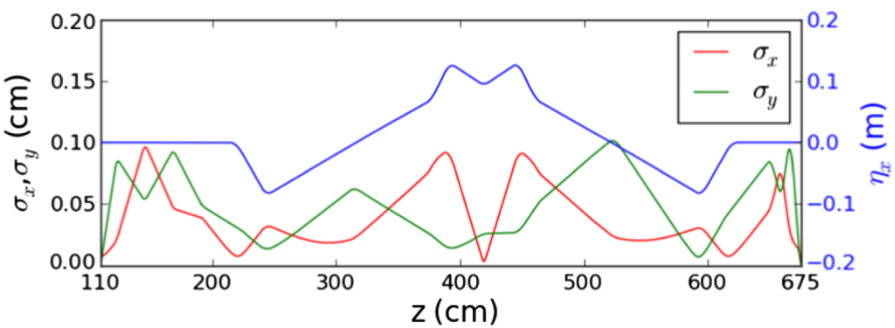
Redefine beta function and dispersion function in space charge dominated regime

- **Turn on space charge**: **beta function and dispersion function loss meaning; 3-D blow up;**
- Redefine:

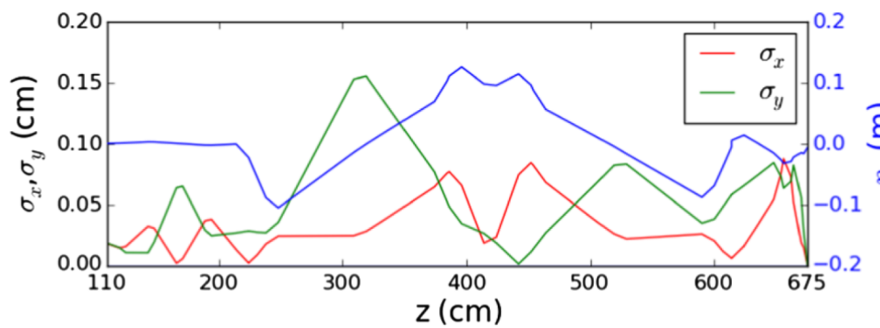
  equivalent **beta functions** using RMS beam size in **selected initial emittance ranges**

  equivalent **dispersion** by averaging the trajectory in **selected initial energy ranges**
- Gradually increase charge and adjust quads to **restore "dispersion function" and "beta function"** to the same as the case without space charge

- 30 pC without blowing up, without losing particles (~ 700 fs)



Linear lattice functions along compressor without space charge effects from code OptiM



Nonlinear redefined functions with 50 pC space charge effects from code PARMELA

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Global optimization using genetic algorithm

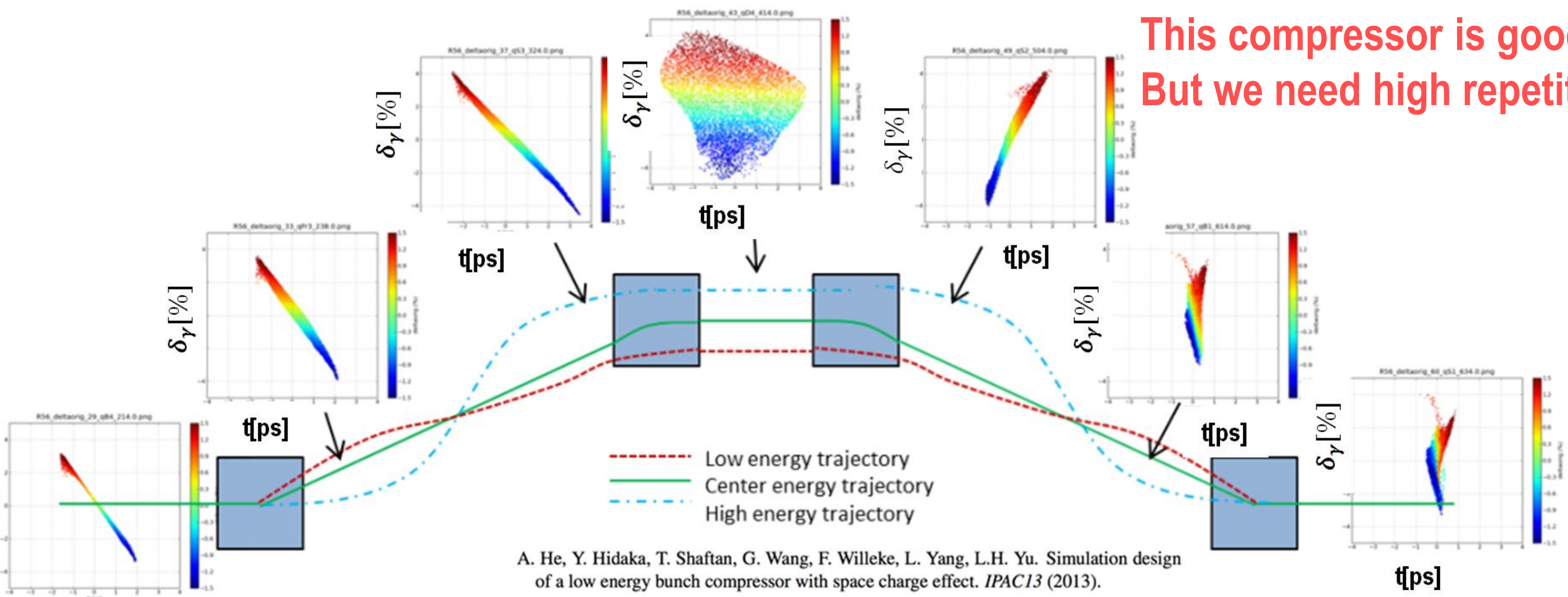
- **Variables**: laser pulse length, laser phase, solenoid strength, field strengths of magnets, etc.
- **Optimized objects**: bunch length, sum of transverse RMS beam sizes.
- **Constrains**: survival particle number

Thanks Dr. Lingyun Yang for the optimizer

- **Set the limits of variables** to reduce parameter scanning phase space.
- **Iterate the optimization** by using new range from last results.
- **Gradually increase charge** from 30 pC to 50 pC.
- Result: at 5MeV, 50pC, ~7m compressor ----> 1.27ps, 2mm, 2mm to **166 fs, 28 μm, 31 μm** .

Longitudinal phase space evolves during bunch compression

This compressor is good,
But we need high repetition rate



A. He, Y. Hidaka, T. Shaftan, G. Wang, F. Willeke, L. Yang, L.H. Yu. Simulation design of a low energy bunch compressor with space charge effect. *IPAC13* (2013).

Benchmark and CSR effects

- **Why design another compressor?**

Thanks Dr. Ji Qiang for his generous guidance on the application of IMPACT-T & IMPACT-Z

High repetition rate: BNL RF-gun (1~10Hz) -> LBNL VHF RF-gun (186MHz)

CSR (coherent synchrotron radiation**) effects: PARMELA -> IMPACT-T**

bench mark the results between code PARMELA and IMPACT-T

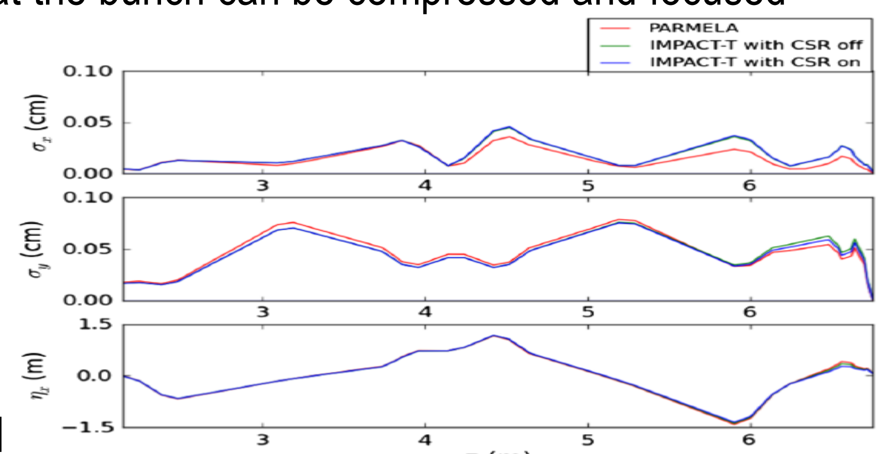
- **Verify our simulation results:**
  - **Benchmark** results between **IMPACT-T and PAMELA** for our linac compressor.

    -> simulation results of two codes agree well
  - Compare the simulation results when **CSR effects** turning on with that when turning off in IMPACT-T.

    -> the CSR effects comparison shows that the bunch can be compressed and focused

TABLE III. The benchmark results of PARMELA against IMPACT-T and the comparison of CSR turning off with CSR turning on in IMPACT-T. We take the optimized 12 MeV, 150 pC bunch compressor of case 3 in Table II as an example to do the benchmark and comparison.

Code	CSR effects	$\sigma_L{}^{a}$ [fs]	$\sigma_H{}^{a}$ [μm]	$\sigma_V{}^{a}$ [μm]
PARMELA	Off	145	35	24
IMPACT-T	Off	137	45	32
IMPACT-T	On	157	41	26



Low energy bunch compressor with VHF gun

- **Change gun** into LBNL's VHF gun (operated at 186MHz with 1MHz repetition rate), add two 1.3 GHz TESLA-like superconducting cavities.
- **Match beta functions** with those at the upstream of chicane at 13 MeV
- to increase bunch's charge and energy

  to scaling increase the strength of chicane magnets

  global optimization procedure using genetic algorithm

TABLE I. Performances of the compressor.

Case	Charge [pC]	Energy [MeV]	σ_L[a] [fs]	σ_H[b] [μm]	σ_V[c] [μm]
1	150	18	130	47	28
2	200	20	148	46	25
3	200	22	128	42	25

Optimized results of the two compressors

TABLE II. Examples of the optimized results for the two low energy compressor.

compressor		with BNL gun (6.77 m long)		with LBNL VHF gun (8.74 m long)	
bunch performance		initial bunch	focused[a] bunch	initial bunch	focused[a] bunch
longitudinal bunch length [fs]		1270[b]	166[c]	6783[d]	128[c]
horizontal beam size [μm]		2000[b]	31[c]	1994[d]	42[c]
vertical beam size [μm]		2000[b]	28[c]	1971[d]	25[c]
energy spread [%]	$\Delta E/E$	0.09[e]	0.93	0.0014[e]/0.98[f]	1.38
average kinetic energy [MeV]	E	4.69[e]	4.69	0.73[e]/22[f]	22
horizontal emittance [μm]	ε_x	0.177[e]	1.02	59[e]/0.143[f]	0.71
vertical emittance [μm]	ε_y	0.189[e]	0.84	58.5[e]/0.142[f]	0.19
charge [pC]	Q	50	50	200	200

compressed ratio

26

47

79

[a] be calculated for 90% of particles, with 10% tails cut off.
[b] at cathode: longitudinal distribution is Gaussian with $2\sigma_z$=1.27 ps; transver distribution is uniform with the same radius of 2 mm.
[c] RMS value
[d] at cathode: longitudinal distribution is flat-top with linear ramp at two ends total length from head to tail is 6.78 ps; transverse distribution is uniform ell with hard cut edge, the diameter of the ellipse in x and y is 1.99 mm.
[e] at gun exit
[f] after RF acceleration

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Design of low energy bunch compressors with space charge effects

A. He, F. Willeke, L. H. Yu, L. Yang, T. Shaftan, G. Wang, Y. Li, and Y. Hidaka
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(Received 15 August 2014; published 7 January 2015)

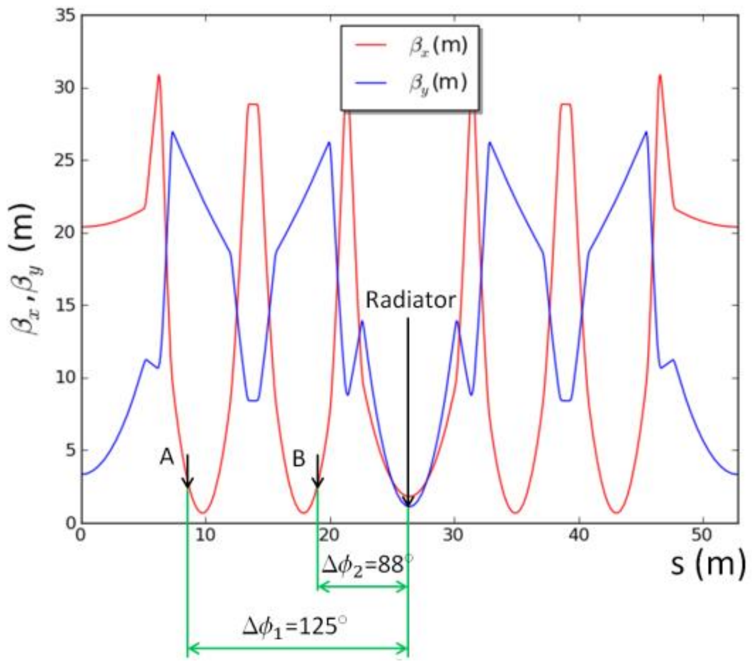
Low energy linac bunch compressor to obtain a very short bunch with low => emittance at low energy

A breakthrough for FEL linac

⇓

Produce two bunches using one linac => HGHG FEL

Kick point in NSLS-II lattice



- Choose maximum β_y to maximize the angular separation of the slice from the core
- Choose minimum β_x to minimize the slice bunch length

point A: $\Delta\phi_A = 125°, \beta_y = 25 \text{ m}, \beta_x = 3.8 \text{ m}$

point B: $\Delta\phi_B = 88°, \beta_y = 25 \text{ m}, \beta_x = 3.8 \text{ m}$

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Slice profile at kicker and radiator

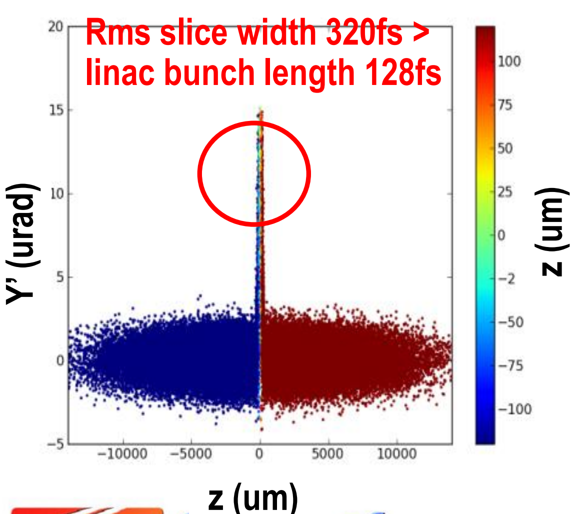
- Calculate slice profile:

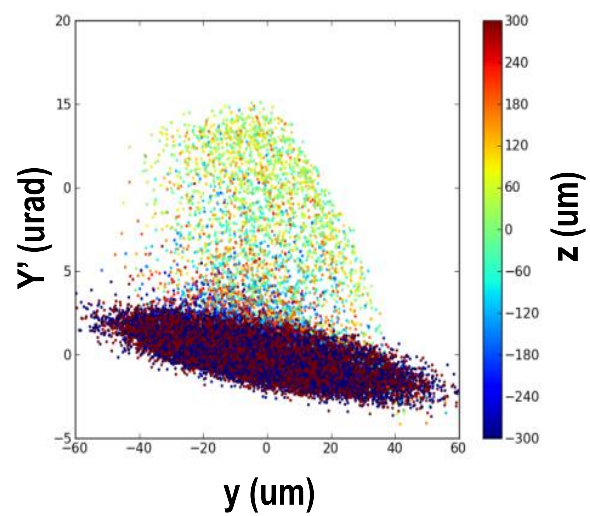
  Using 6D distribution at final focus point from our designed compressor as the simulated linac bunch

- code: ELEGANT (to track the transport of phase space distribution)
- particle number: 10,000 for low energy linac bunch

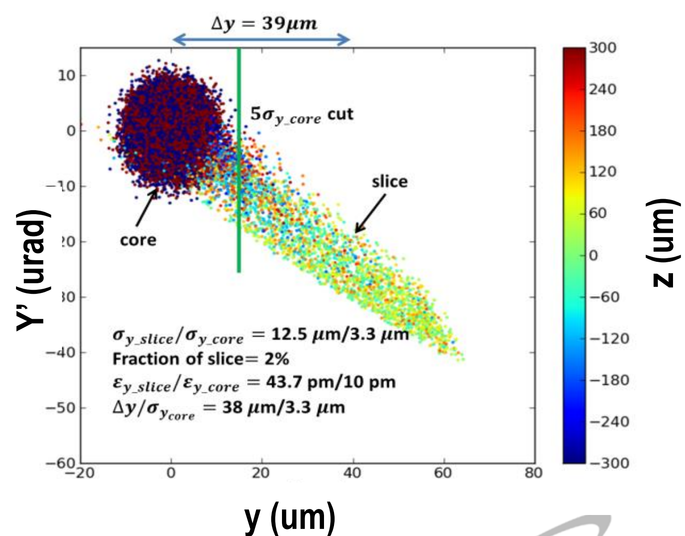
  100,000 for high energy storage ring bunch

Phase spaces right after the kick

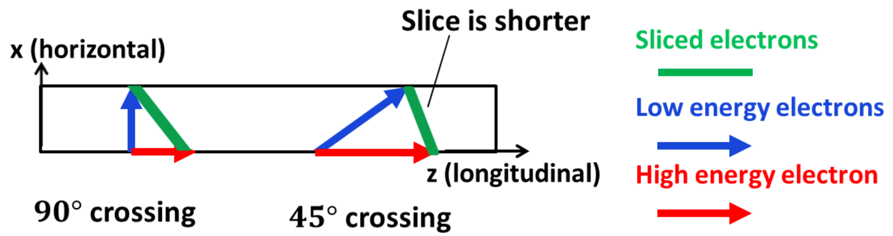


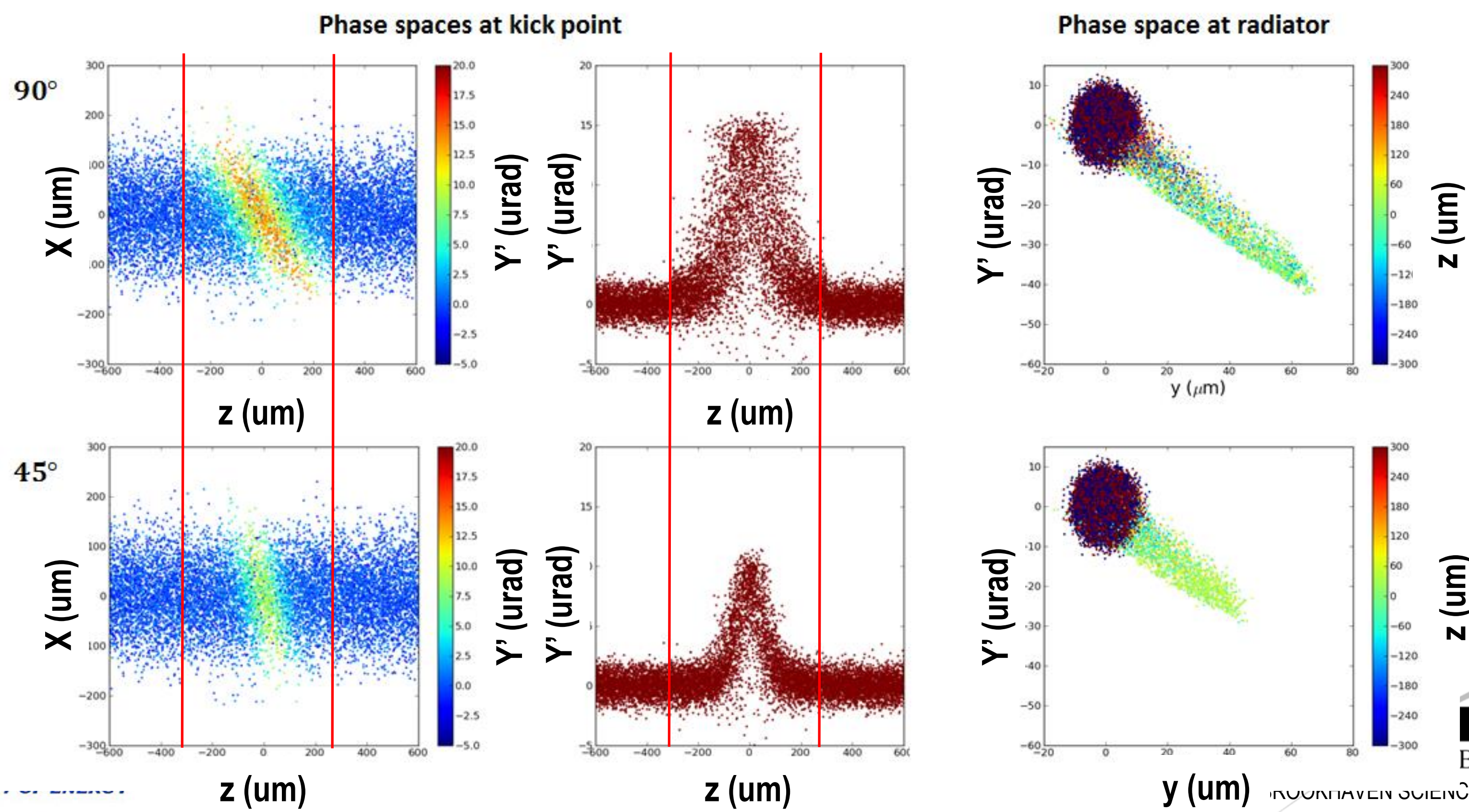


Phase space at the radiator

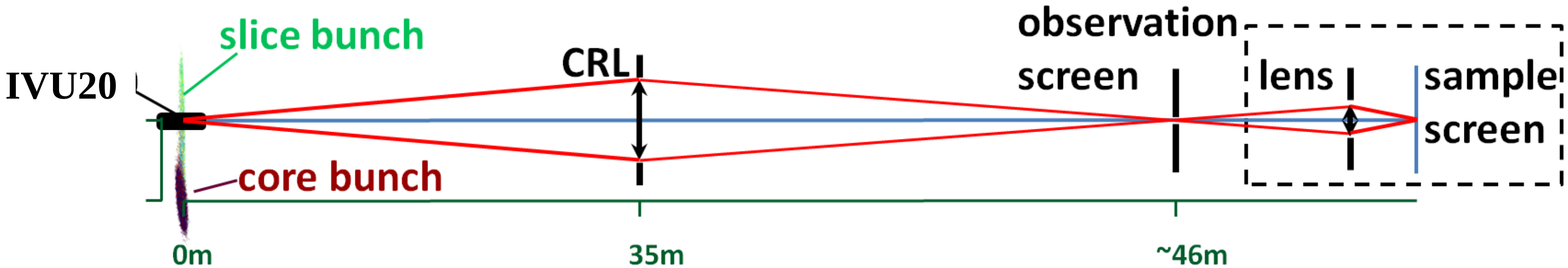


Reducing crossing angle to reduce slice pulse length





Beam line design for radiation separation



- ➢ Angular + spatial hybrid separation
  Pure spatial separation
- ➢ Code: SRW (synchrotron radiation workshop)

Thanks Dr. Oleg Chubar for his generous guidance on the use of SRW and the separation calculation.

A. He, O. Chubar, L.H. Yu. Separation of hard X-ray synchrotron radiation from electron beam slices. to be submitted in *Proc. SPIE* (2014).

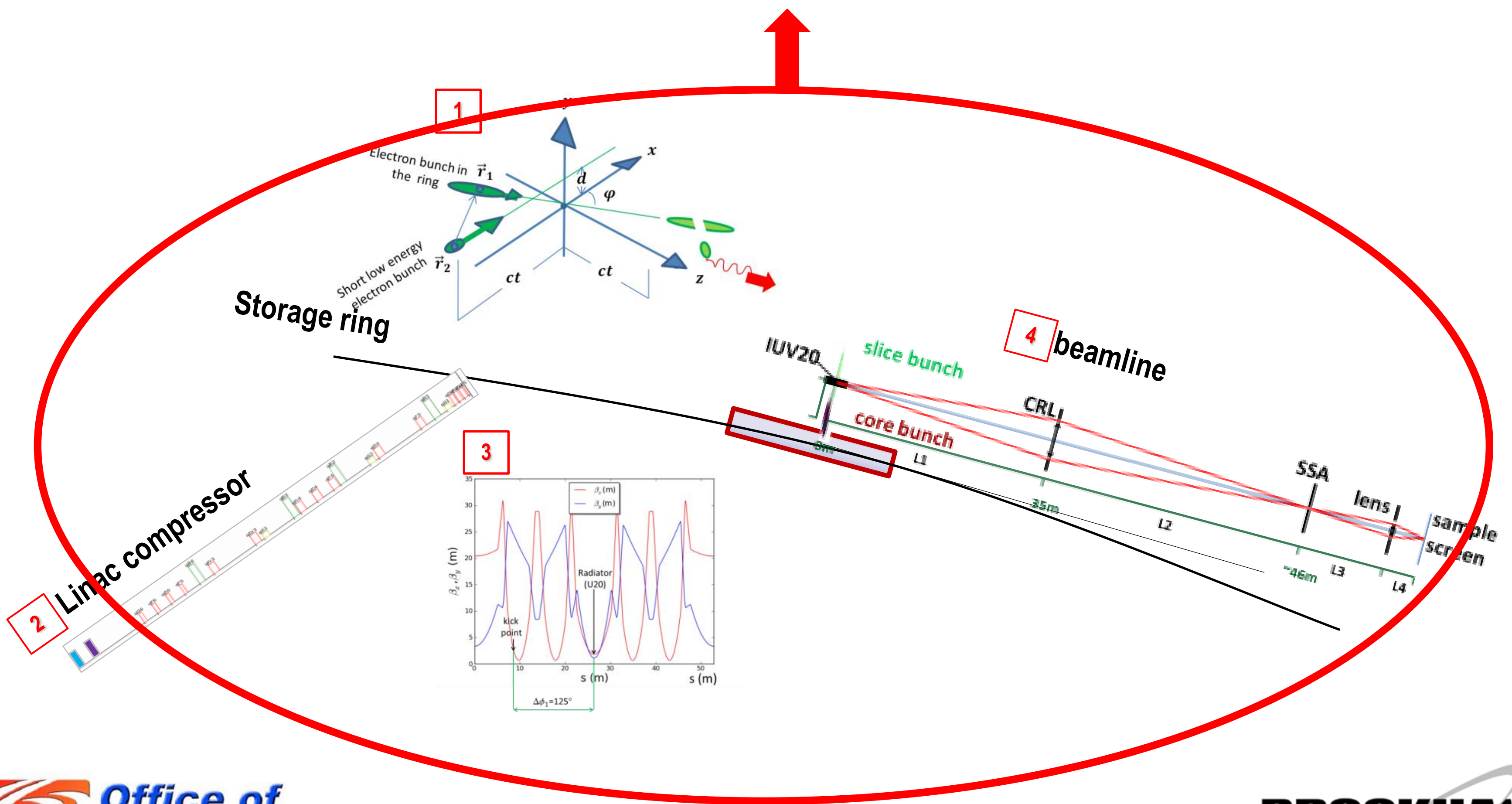
TABLE III. Separation performances of hard x-ray synchrotron radiation from electron beam slices. Data are recorded at 7.8 KeV on the observation screen.

Crossing angle	Separate type	Flux/pulse[a] [photons/0.1%bw]	Flux[b] [photons/ sec /0.1%bw]	Peak intensity [photons/ sec /0.1%bw/mm^2]	SNR	Pulse length [fs]
90°	Spatial + angular	10×10^3	10×10^8	2.1×10^{10}	12	320
	Spatial	18×10^3	18×10^8	6.5×10^{10}	5	320
45°	Spatial + angular	5×10^3	5×10^8	1.1×10^{10}	8[c] (2.6)	150
	Spatial	5×10^3	5×10^8	3.6×10^{10}	8[c] (2.7)	150

[a]Assume NSLS-II's revolution time is about 2.6 μs, then flux/pulse = power × 2.6 μs.
[b]Assume the repetition rate of the low energy linac is 100 kHz, then flux = flux/pulse × 100 kHz.
[c]With 10 ps of the detector's time resolution.

The last issue

System's photon flux and repetition rate ?



Photon flux

- **Estimated photon flux**

U20: 10^{15} photons/sec/0.1%BW (8 keV, 500mA)
ring: current 500 mA, 1000 bunches;
revolution time: 2.6 μs
slice fraction: 0.3 ps/30 ps

single pulse photon flux:
$10^{15} \times 0.3$ ps/30 ps $\times$ 2.6 μs/1000
$= 2.6 \times 10^4$ photons/0.1%BW

- **Simulation results of photon flux (code: SRW)**

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[a]Assume NSLS-II's revolution time is about 2.6 μs, then flux/pulse = power $\times$ 2.6 μs.
[b]Assume the repetition rate of the low energy linac is 100 kHz, then flux = flux/pulse $\times$ 100 kHz.
[c]With 10 ps of the detector's time resolution.

Emittance increase and repetition rate

Estimated emittance increase for a single bunch

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1) induced by one time angular kick: $0.3\ \text{ps}/30\ \text{ps} \times 5^2 \times 1/2\varepsilon_y = 12\%\varepsilon_y$
(assume $5\sigma'_y$ kick with a slice of 300 fs/ 30 ps)

---

2) due to the damping time in storage ring: $12\%\varepsilon_y \times$ damping time (10 ms)

---

3) if a single bunch is kicked with 100 Hz repetition rate: $12\%\varepsilon_y \times 10\ \text{ms} \times 100\ \text{Hz} = 12\%\varepsilon_y$

Distribute the kicks uniformly over all 1000 bunches

↓

Repetition rate 100 kHz, photon flux ~10^9 [photons/sec/0.1%bw]

↓

Repetition rate limit 100 kHz ~ 1MHz, depending on tolerance of the vertical emittance increase

Summary

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Ultrashort x-ray pulse generation by electron beam slicing in storage rings

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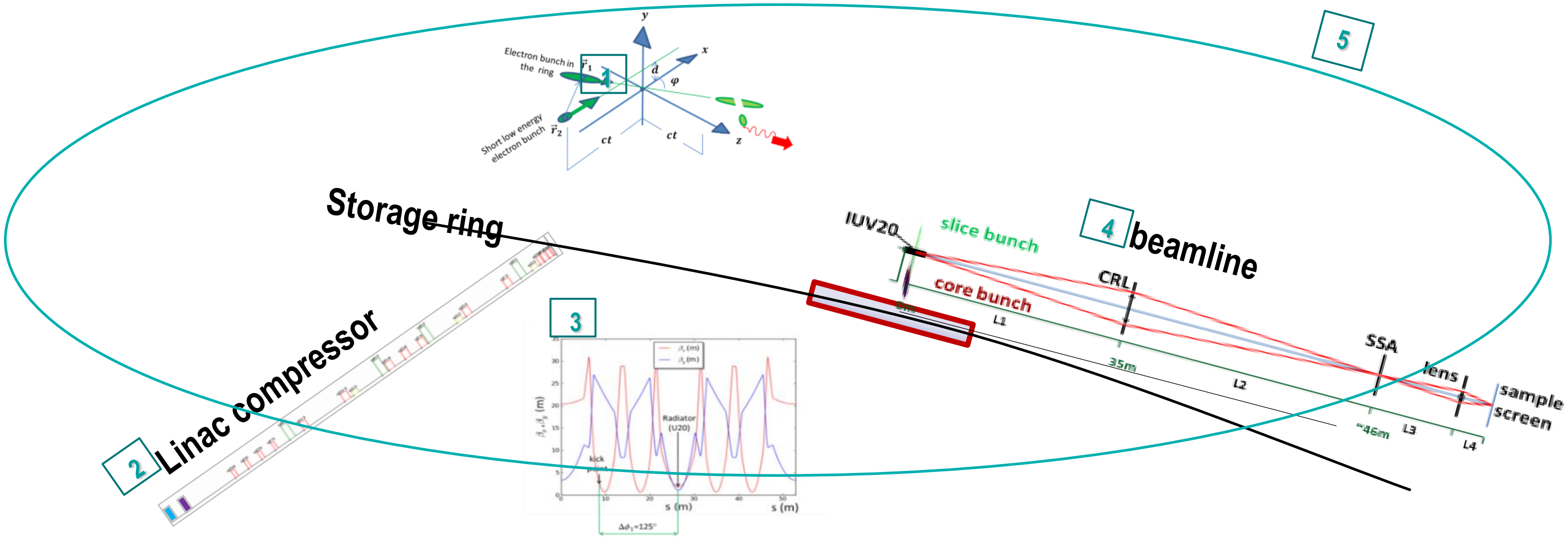

	Laser slicing	Crab cavity	X-ray FEL	Ebeam slicing
source	Storage ring	Storage ring	FEL	Storage ring
Occupied ring space	large	large	large	small
Pulse length	~ 100 fs	~ ps	< 100 fs	~150 fs
Photon flux	~ 10^6 photons/sec/0.1%bw	~ 10^{14} photons/sec/0.1%bw	~ 10^{12} photons/sec/0.1%bw	~ 10^{10} photons/sec/0.1%bw
Repetition rate	1 kHz	100 MHz	Low (120Hz for LCLS)	1 MHz
Pulse to pulse stability	good	good	poor	good

Publications:

BOOK:

[1] A. He, L. Yang, L.H. Yu. Introduction to High-Gain FEL Theory.
(the 1st chapter of book "Synchrotron Light Sources and Free-Electron Lasers", edited by Eberhard Jaeschke, Shaukat Khan et al., in Springer (2014)).

JOURNAL:

[2] A. He, F. Willeke, L.H. Yu, J. Qiang et al., Phys. Rev. ST Accel. Beams 18, 014201(2015).
[3] A. He, F. Willeke, L.H. Yu. Phys. Rev. ST Accel. Beams 17, 120704 (2014).
[4] A. He, F. Willeke, L.H. Yu. Phys. Rev. ST Accel. Beams 17, 040701 (2014).

CONFERENCE:

[5] A. He, O. Chubar, L.H. Yu. Proc. SPIE (2014).
[6] A. He, J. Qiang, F. Willeke, L. Yang, L.H. Yu. FEL14 (2014).
[7] A. He, F. Willeke, L.H. Yu. FEL14 (2014).
[8] A. He, Y. Hidaka, T. Shaftan et al., IPAC13 (2013).

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