Bunch compression for the ultra-compact x-ray free-electron laser

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Stanford University and SLAC

C^3 Workshop

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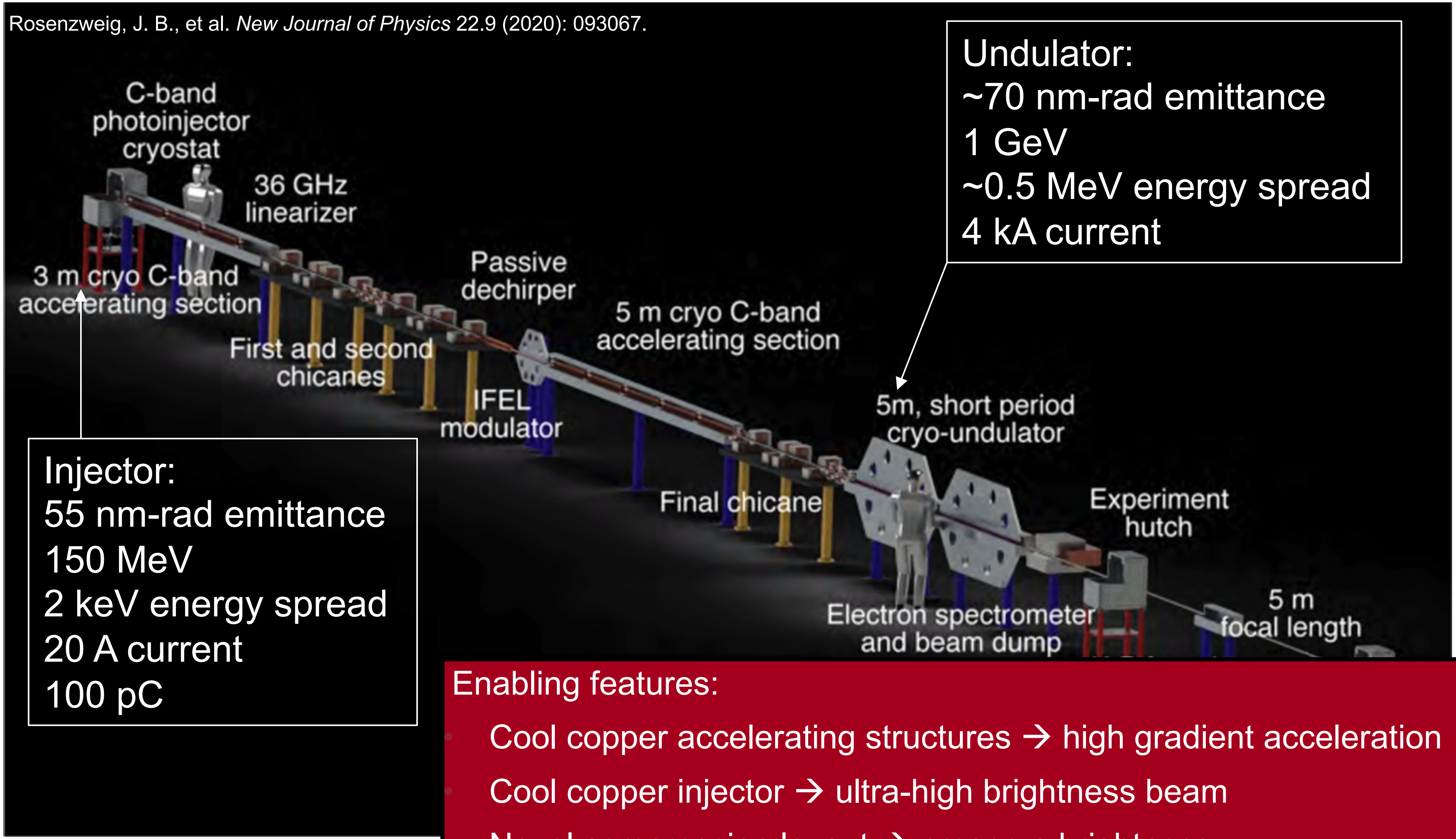
The Ultra-Compact X-ray Free-Electron Laser (UCXFEL)



Rosenzweig, J. B., et al. *New Journal of Physics* 22.9 (2020): 093067.

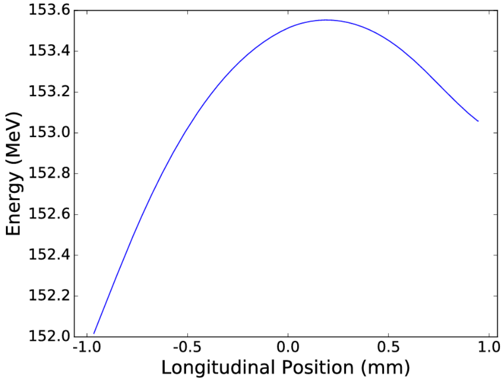
Undulator:
~70 nm-rad emittance
1 GeV
~0.5 MeV energy spread
4 kA current

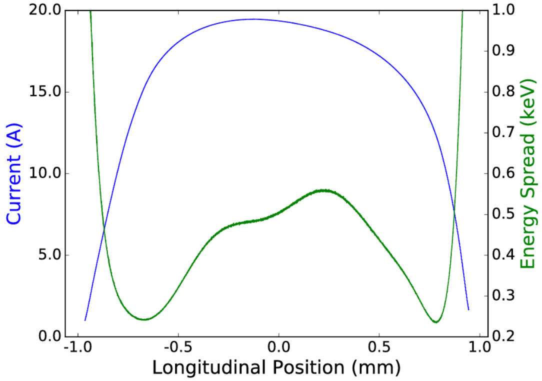
Injector:
55 nm-rad emittance
150 MeV
2 keV energy spread
20 A current
100 pC

Enabling features:

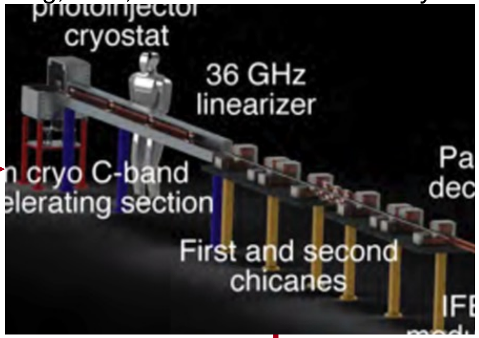
- Cool copper accelerating structures → high gradient acceleration
- Cool copper injector → ultra-high brightness beam
- Novel compression layout → preserve brightness

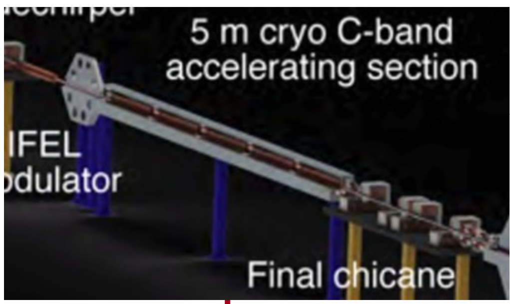
Compression stages in more detail

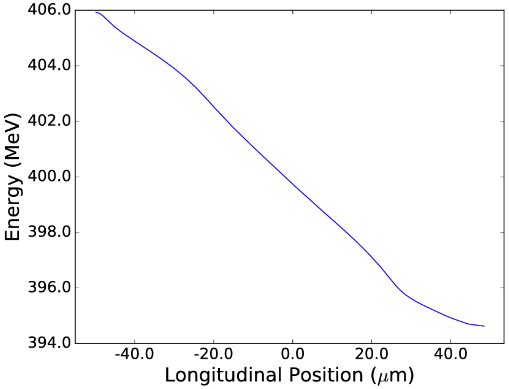


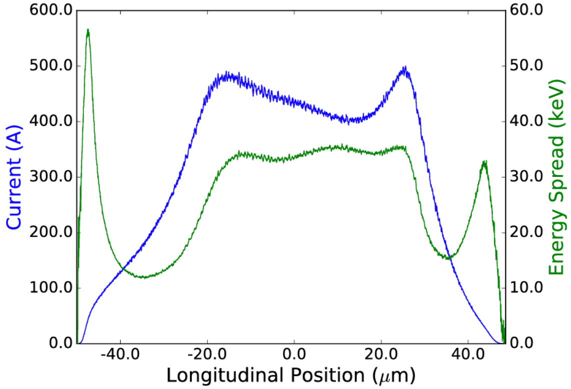


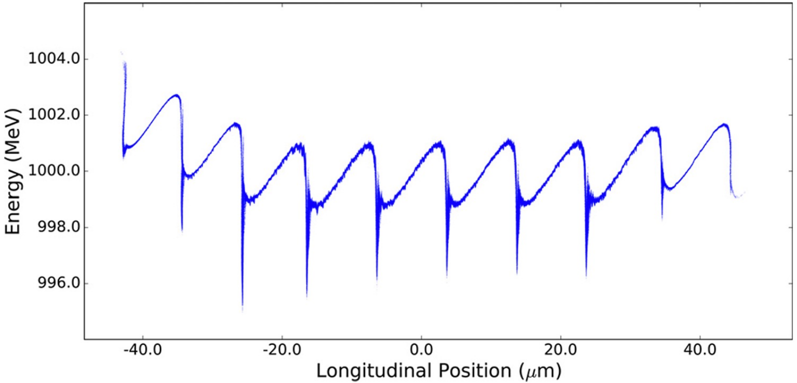
Rosenzweig, J. B., et al. *New Journal of Physics* 22.9 (2020): 093067.

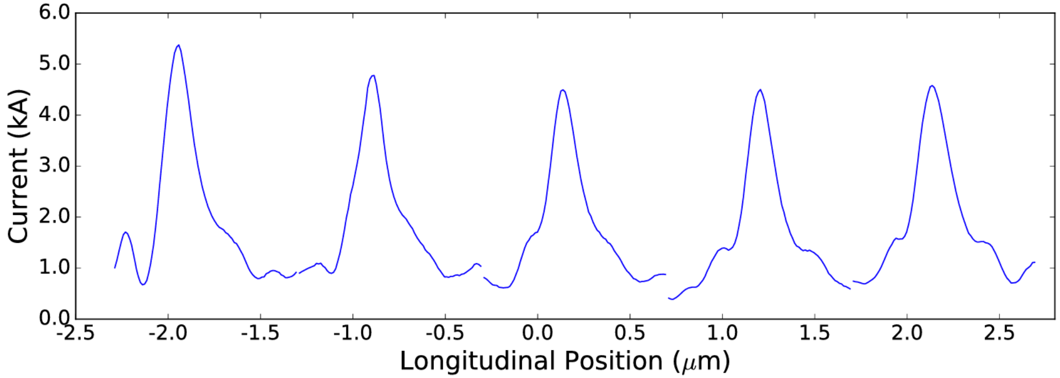






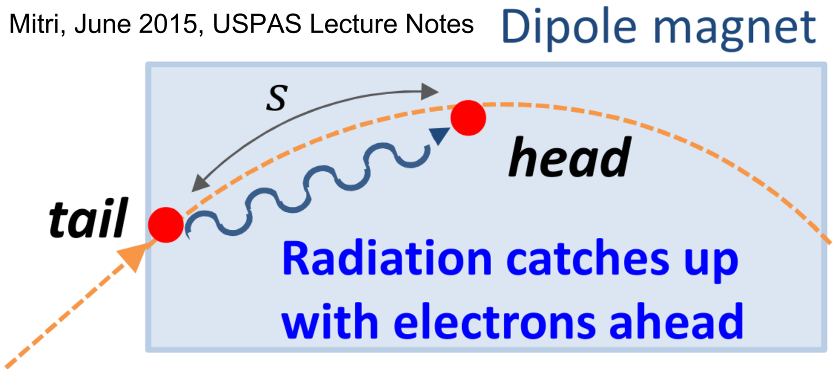




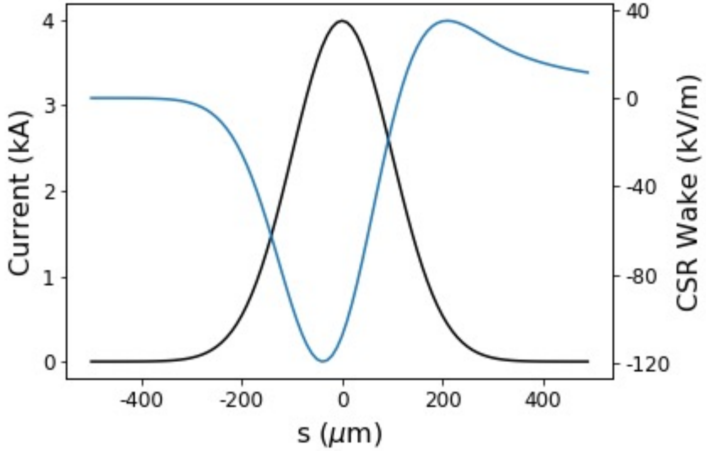


Coherent synchrotron radiation (CSR)

S. Di Mitri, June 2015, USPAS Lecture Notes

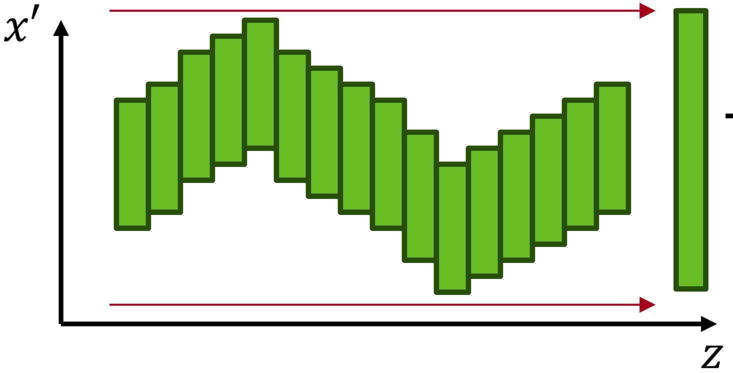


Radiation catches up with electrons ahead



Correlated energy kicks in dispersive region → temporal-angular correlations → emittance growth

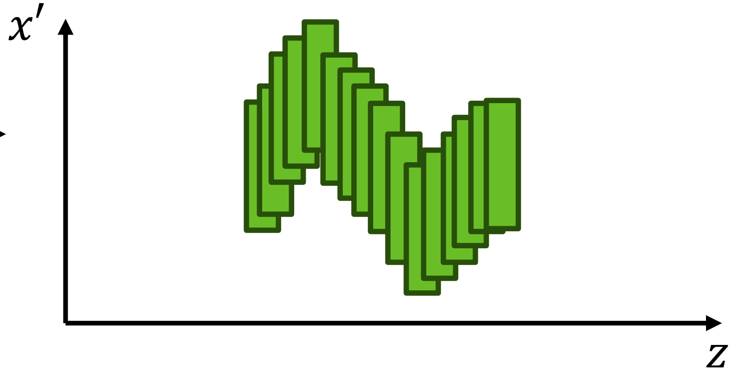
Projected emittance growth



Reversible in principle with the right correlated kicks

Further compression →

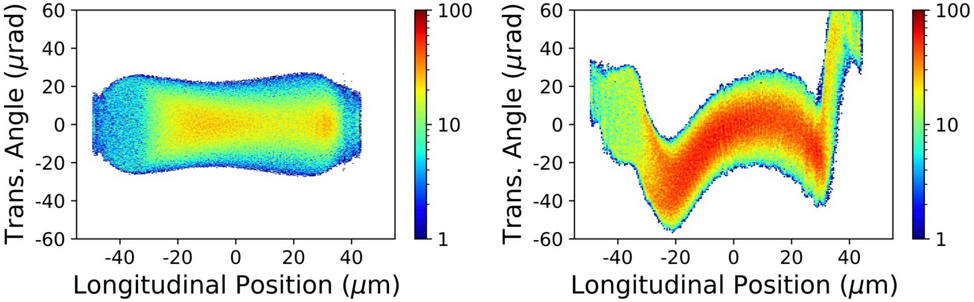
Slice emittance growth

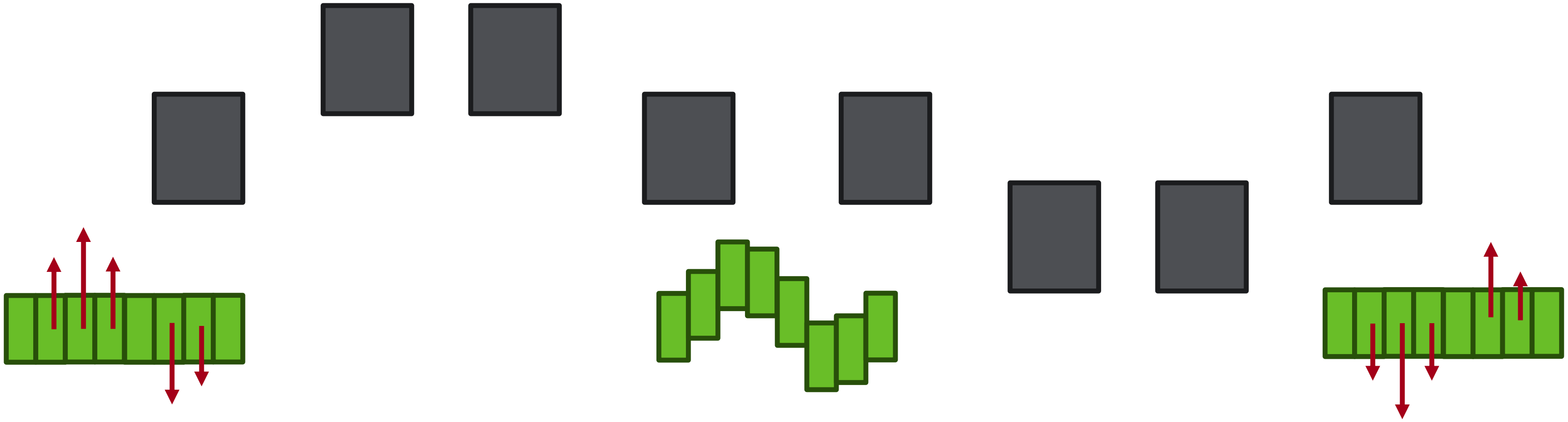


Practically irreversible

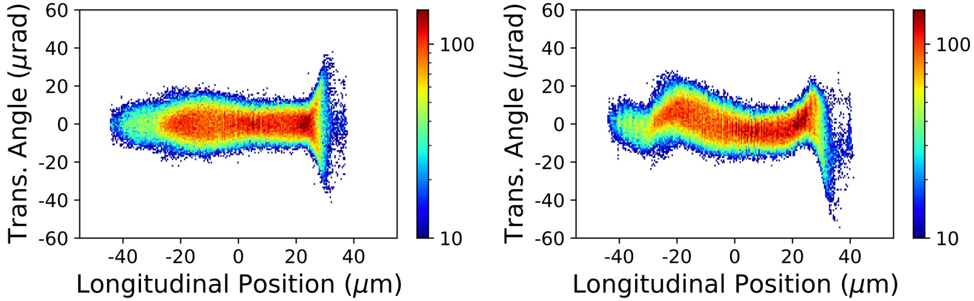
First compressor: zig-zag chicanes

Single chicane ("C-chicane") design:
112 nm-rad projected emittance





Zig-zag chicane ("S-chicane") design:
65 nm-rad projected emittance



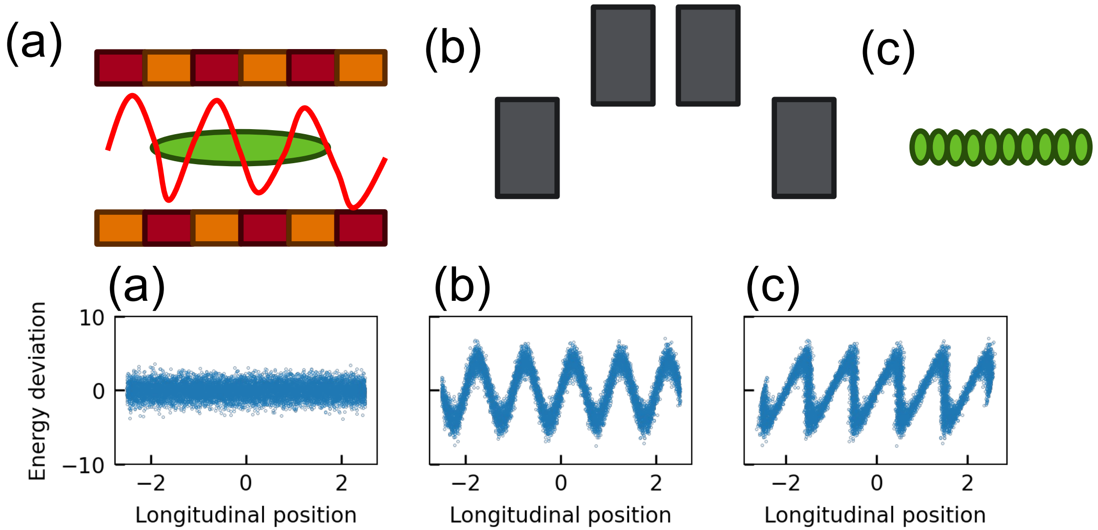
Jing, Yichao, Yue Hao, and Vladimir N. Litvinenko. *PRSTAB* 16.6 (2013): 060704.
Robles, River, and James Rosenzweig. *Instruments* 3.4 (2019): 53.

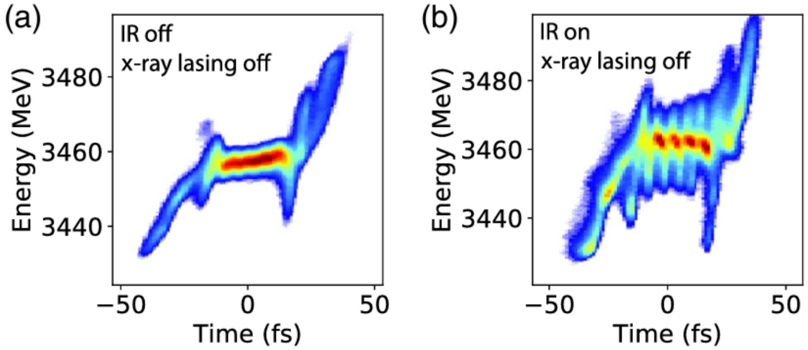
Second compressor: laser-based compression

CSR energy spread:

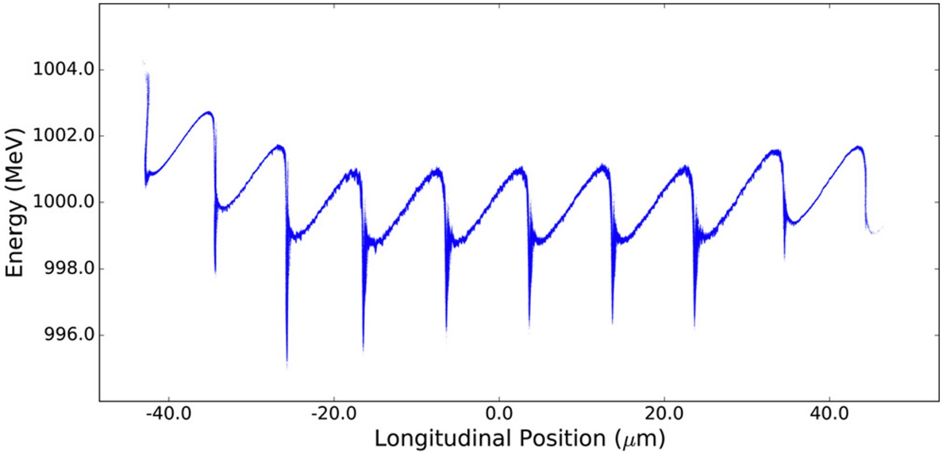
$$\Delta\gamma \simeq 0.22 N_e r_e \left(\frac{L_b \theta^2}{\sigma_z^4}\right)^{\frac{1}{3}}$$

→ minimize R_{56} → maximize chirp



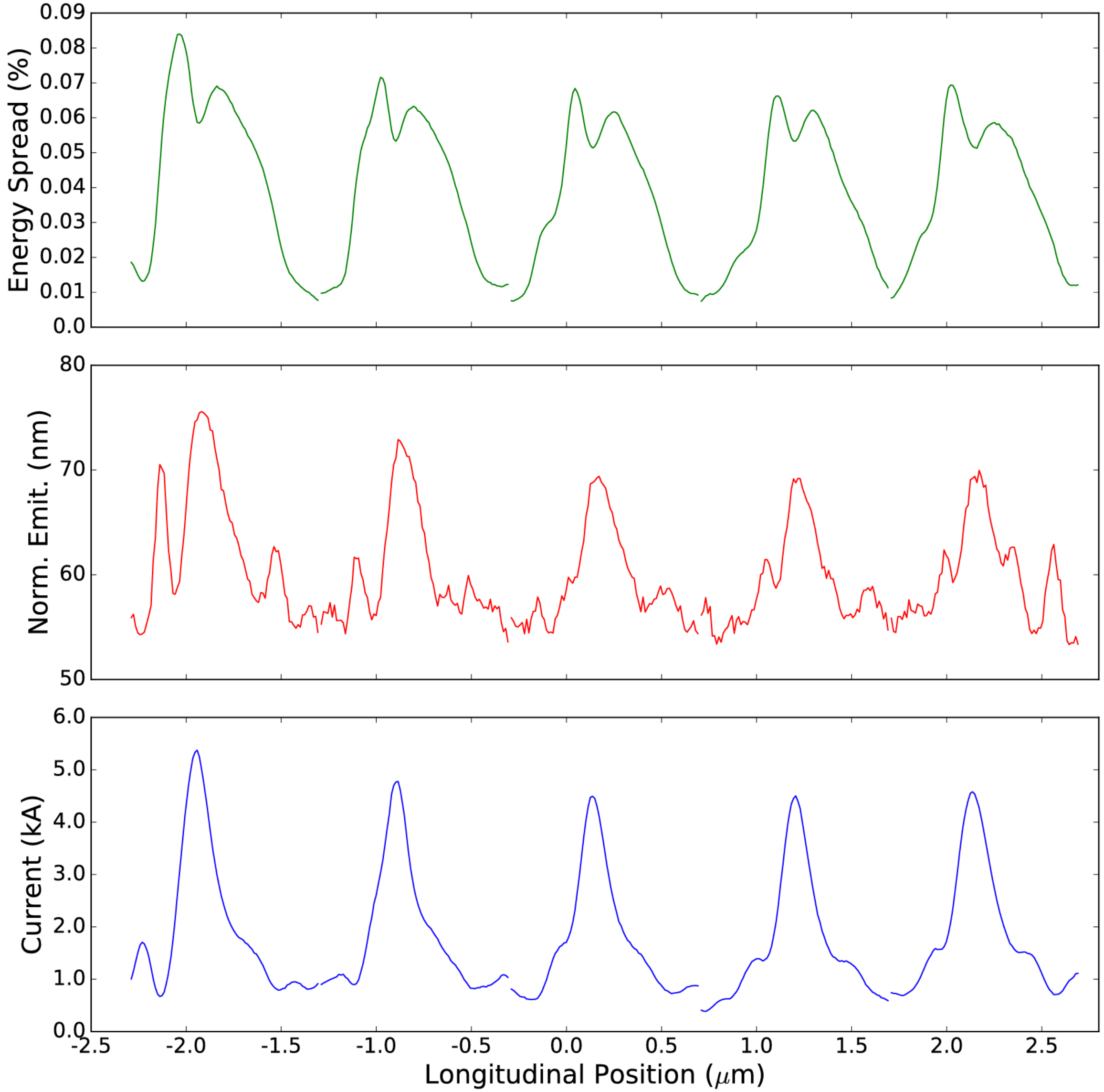


Reproduced from Duris, Joseph P., et al. *Physical Review Letters* 126.10 (2021): 104802.



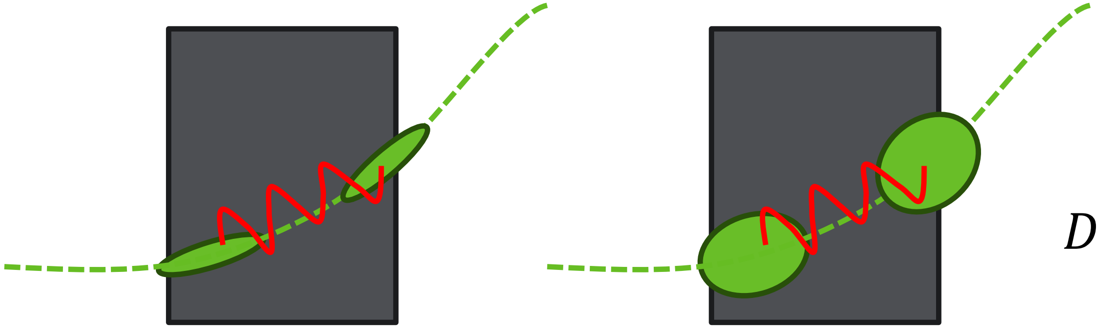
Zholents, Alexander A. *PRSTAB* 8.4 (2005): 040701.

Microbunch features



Rosenzweig, J. B., et al. "*New Journal of Physics* 22.9 (2020): 093067.

Three-dimensional CSR effects for short bunches

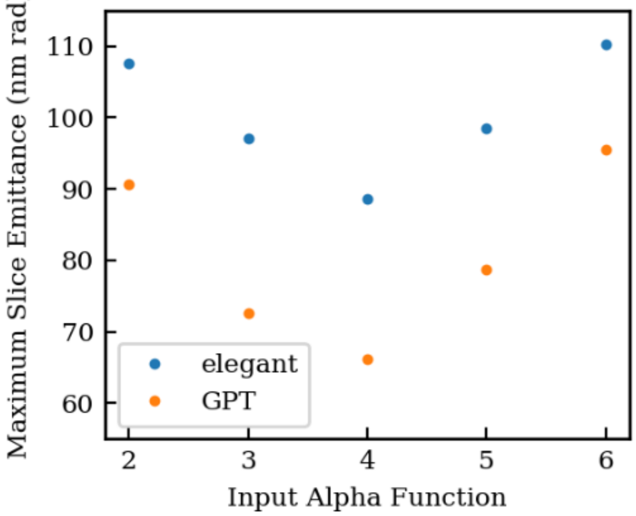


What quantifies the regime?
Derbenev criterion:

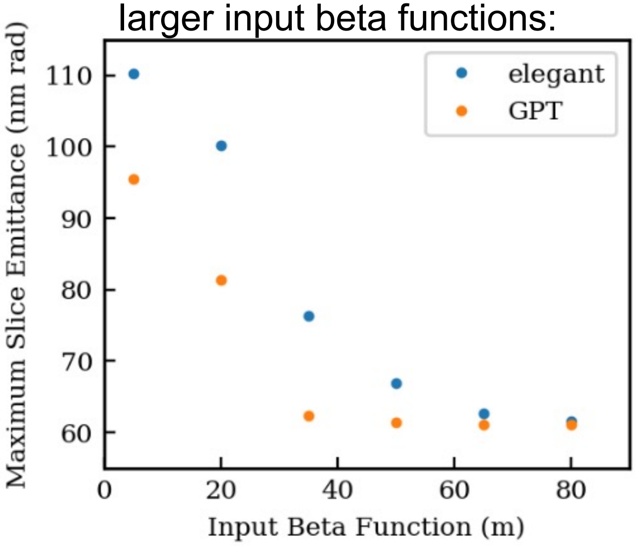
$$D = \frac{\sigma_r}{(R\sigma_z^2)^{\frac{1}{3}}} \quad \begin{array}{lll} \geq 1 & \rightarrow & \text{3D} \\ \ll 1 & \rightarrow & \text{1D} \end{array}$$

How does 3D CSR affect the UCXFEL case? – Study with GPT simulations of a single microbunch

Optimal working point for given beta function unchanged:



Better agreement (and smaller emittances) found for larger input beta functions:



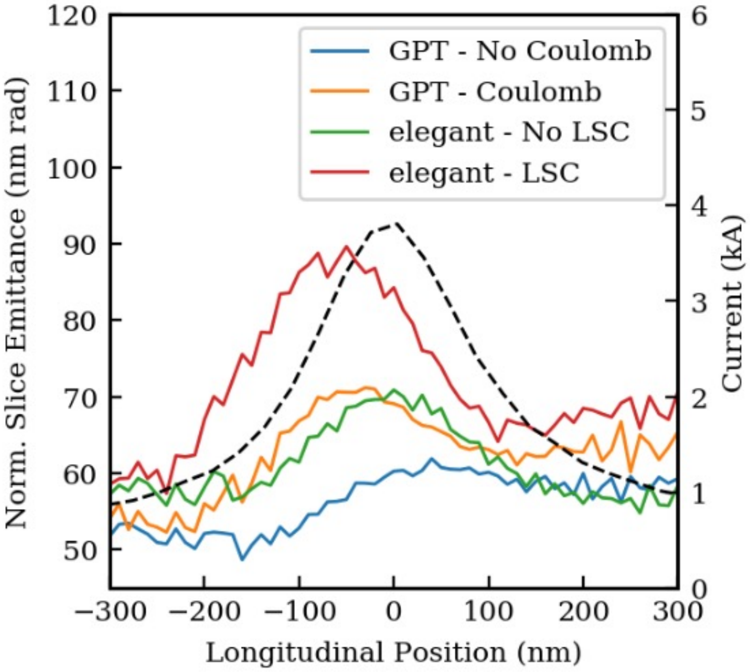
Derbenev, Yaroslav S., et al. *Microbunch radiative tail-head interaction*. No. TESLA-FEL-95-05. SCAN-9511114, 1995.
R. R. Robles, *et al*. Three-dimensional radiative effects in the compression of ultra-short electron micro-bunches. Proceedings of *IPAC 2021* (2021).

What’s happening?

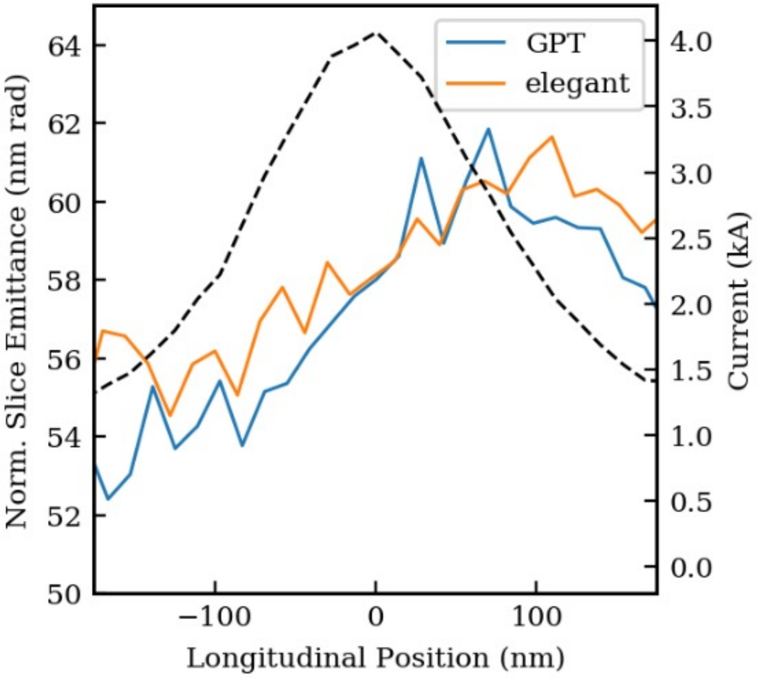
“Velocity term” “Radiation term”

$$\vec{E}(\vec{r}, t) = \frac{e}{4\pi\epsilon_0}\left(\frac{\vec{n} - \vec{\beta}'}{\gamma^2(1 - \vec{n}\cdot\vec{\beta}')^3\rho^2} + \frac{\vec{n} \times ((\vec{n} - \vec{\beta}') \times \dot{\vec{\beta}}')}{c(1 - \vec{n}\cdot\vec{\beta}')^3\rho}\right)$$

10 meter input beta function:



80 meter input beta function:



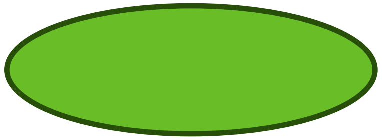
Brynes, A. D., et al. *New Journal of Physics* 20.7 (2018): 073035.

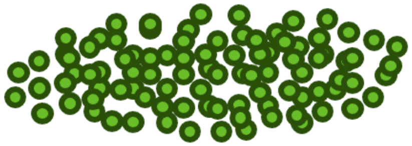
R. R. Robles, *et al*. Three-dimensional radiative effects in the compression of ultra-short electron micro-bunches. Proceedings of *IPAC 2021* (2021).

A cautionary tale about energy spread: intrabeam scattering

We only understand bunch compression limits insofar as we understand our energy spread

$$\sigma_{z,min} = \sigma_{z,0} \frac{\sigma_\delta}{\sqrt{\sigma_\delta^2 + h^2 \sigma_{z,0}^2}}$$



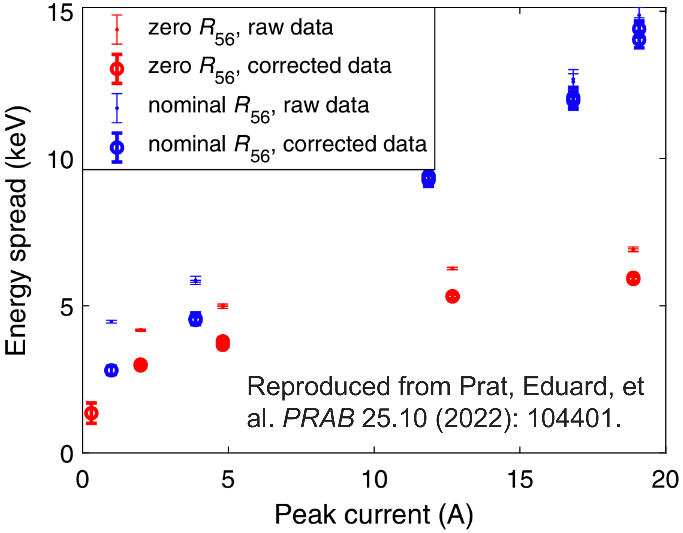


Smooth, mostly correlated space-charge forces
High-frequency noise → microbunching instability

Stochastic collisions give rise to uncorrelated energy spread growth

	PITZ	EUXFEL	SwissFEL
Charge (pC)	250	250	200
Energy (MeV)	20	130	100
Current (A)	20	20	20
Energy Spread (keV)	2.1	5.9	15

Simulations generally < 1 keV from injector



Reproduced from Prat, Eduard, et al. *PRAB* 25.10 (2022): 104401.

Tomin, Sergey, et al. *PRAB* 24.6 (2021): 064201.
Qian, Houjun, et al. *PRAB* 25.8 (2022): 083401.
Prat, Eduard, et al. *PRAB* 23.9 (2020): 090701.

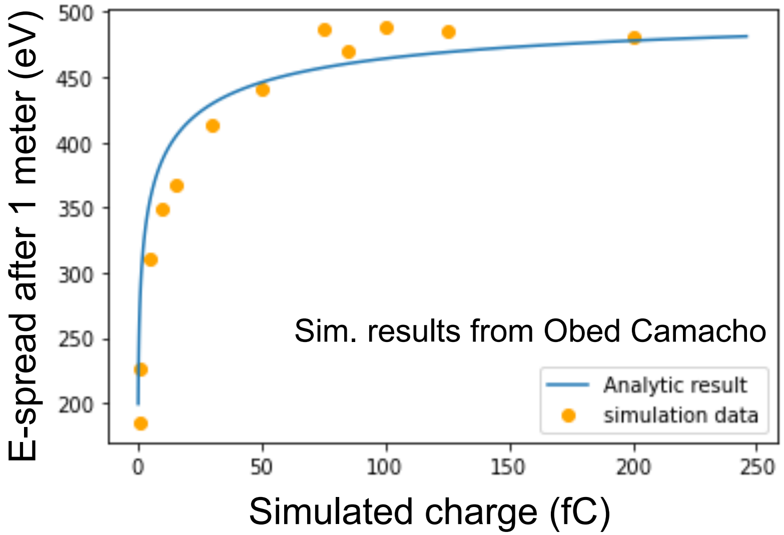
Modeling intrabeam scattering effects

Low energy: scaling arguments

In injector, beam envelope follows:

$$\sigma_x'' + \frac{\gamma'}{\gamma}\sigma_x + \frac{\eta}{8}\left(\frac{\gamma'}{\gamma}\right)^2 \sigma_x = \frac{I}{2I_A\gamma^3\sigma_x}$$

If we scale this while holding $\frac{Q}{\sigma_x\sigma_y\sigma_z}$ constant, we can put it in a form that is independent of the charge



Robles, River R., et al. *PRAB* 24.6 (2021): 063401.

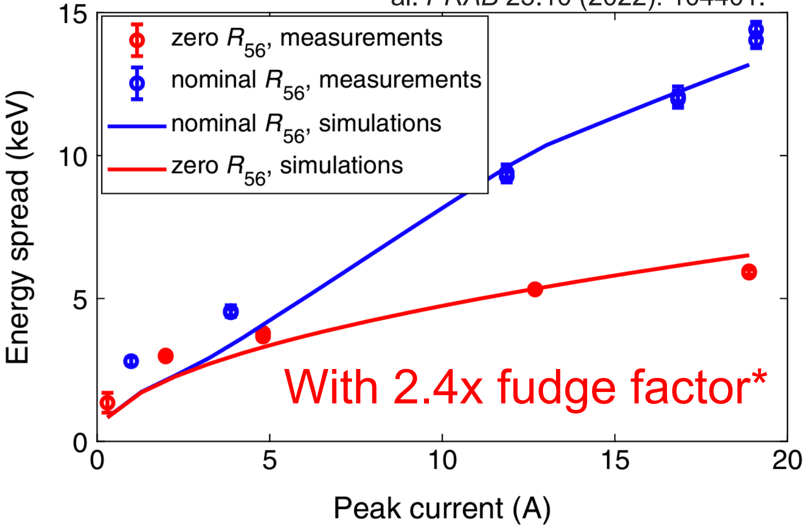
High energy: Piwinski formula

The following formula is often borrowed from older studies on IBS in rings:

$$\frac{\mathrm{d}\sigma_\gamma^2}{\mathrm{d}t} = \frac{r_e^2 cN}{4\epsilon_{nx}\sigma_x\sigma_z}\log\left(\frac{q^2\epsilon_x^2}{4\sigma_x^2}\right)$$

The "coulomb log" is typically ~ 1-20 for relevant beam conditions

Reproduced from Prat, Eduard, et al. *PRAB* 25.10 (2022): 104401.



With 2.4x fudge factor*

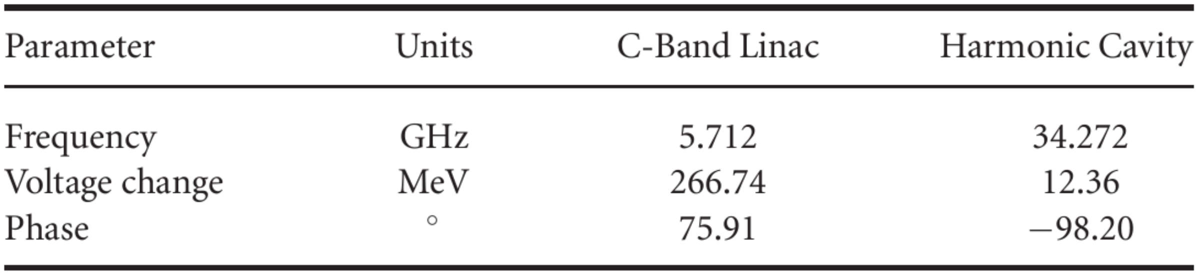
A. Piwinski, in Proceedings of the 9th International Conference on High Energy Accelerators, Stanford, CA, USA,1974,p.405.
Huang, Z. SLAC-TN-05-026 (2002).

Conclusions

- The UCXFEL has two key challenges that require innovative approaches to CSR mitigation:
  - Starting from ultra-low emittance beams
  - Requiring kA compression at relatively low energies
- Zig-zag chicanes can cancel correlated CSR kicks, avoiding projected emittance growth
- Laser modulation enables large chirps with relatively low energy spreads
- 3D CSR can be helpful or harmful, but should be quantified. Seems to have the same working points as 1D from a design perspective
- Sources of uncorrelated energy spread (IBS, MBI) still poorly understood and require better modeling approaches

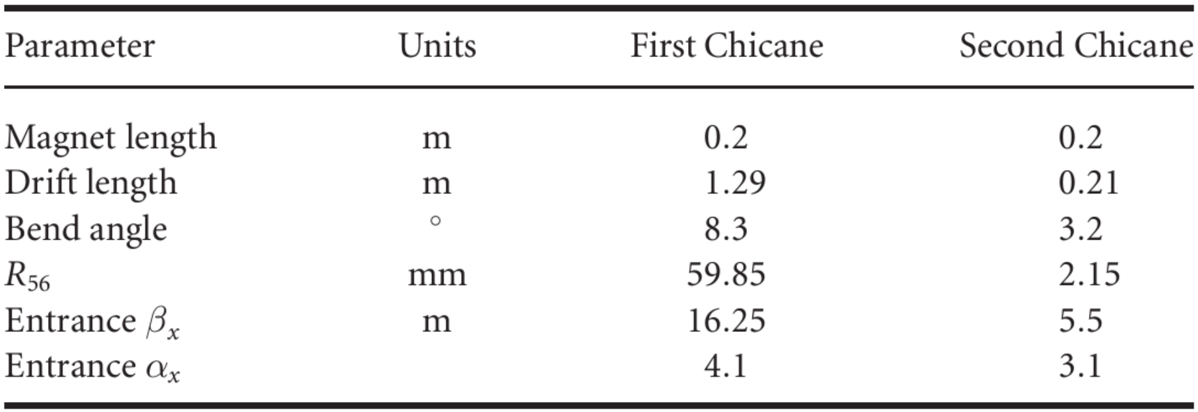
Specific numbers for first compressor

Table 2. Parameters for the first linac section and linearizing cavity.



Parameter	Units	C-Band Linac	Harmonic Cavity
Frequency	GHz	5.712	34.272
Voltage change	MeV	266.74	12.36
Phase	°	75.91	−98.20

Table 3. Parameters for the chicanes of the first bunch compressor.



Parameter	Units	First Chicane	Second Chicane
Magnet length	m	0.2	0.2
Drift length	m	1.29	0.21
Bend angle	°	8.3	3.2
R_{56}	mm	59.85	2.15
Entrance β_x	m	16.25	5.5
Entrance α_x		4.1	3.1

Specific numbers for second compressor

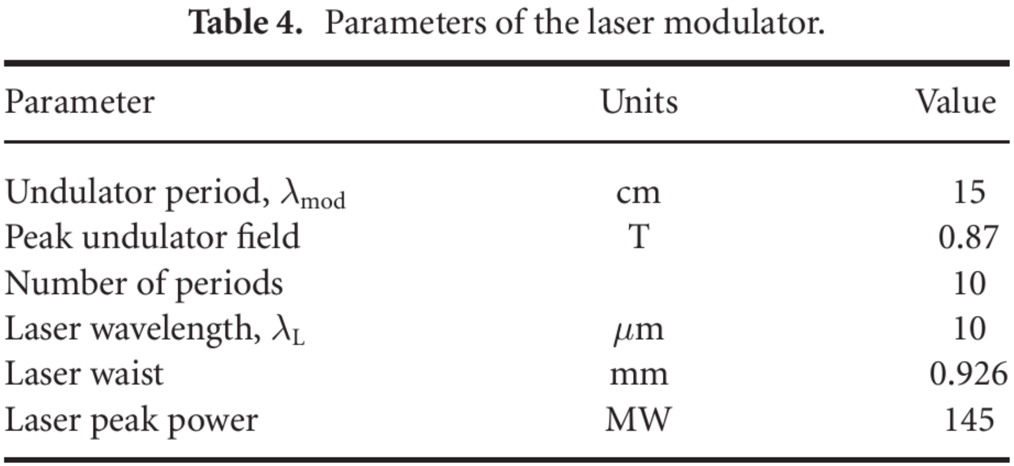


Table 4. Parameters of the laser modulator.

Parameter	Units	Value
Undulator period, λ_{mod}	cm	15
Peak undulator field	T	0.87
Number of periods		10
Laser wavelength, λ_{L}	μm	10
Laser waist	mm	0.926
Laser peak power	MW	145

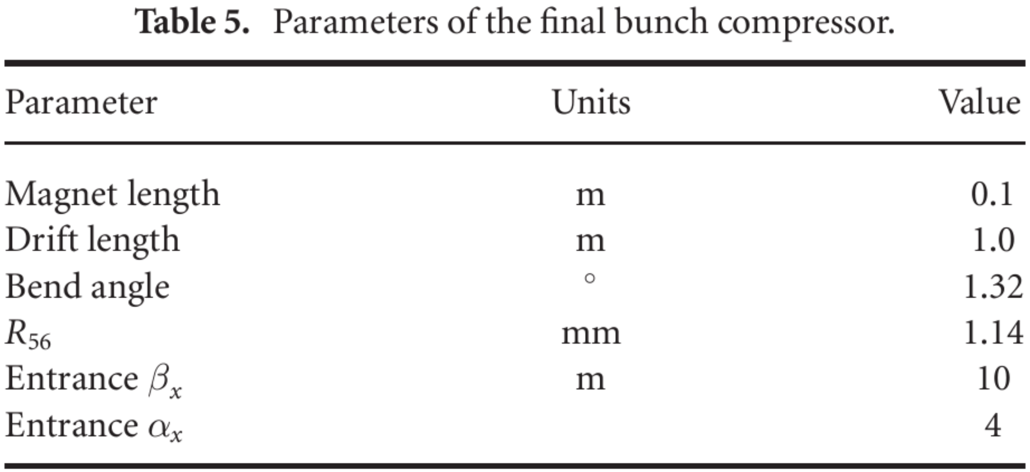


Table 5. Parameters of the final bunch compressor.

Parameter	Units	Value
Magnet length	m	0.1
Drift length	m	1.0
Bend angle	°	1.32
R_{56}	mm	1.14
Entrance β_x	m	10
Entrance α_x		4