Beam on Demand for Superconducting Based Free-Electron Lasers

To enhance the multiplexing of FEL facilities

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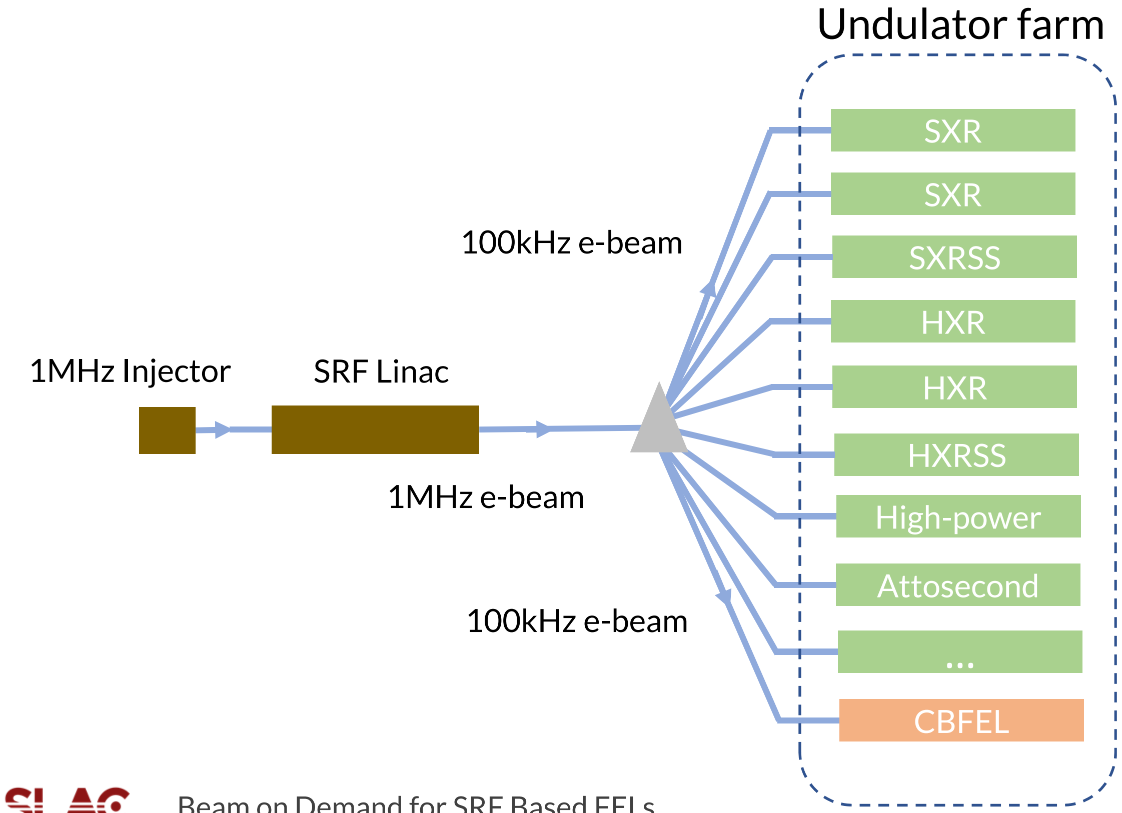
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Motivation of “beam on demand”

To enhance the multiplexing of FEL facility

- MHz e-beams from SRF linac can support multiple undulator lines simultaneously
- The wide-ranging requirements for the photon properties from multiple undulator lines demand more challenging beam manipulation techniques.



Increase facility **multiplexing** and keep high **flexibility** of photon properties

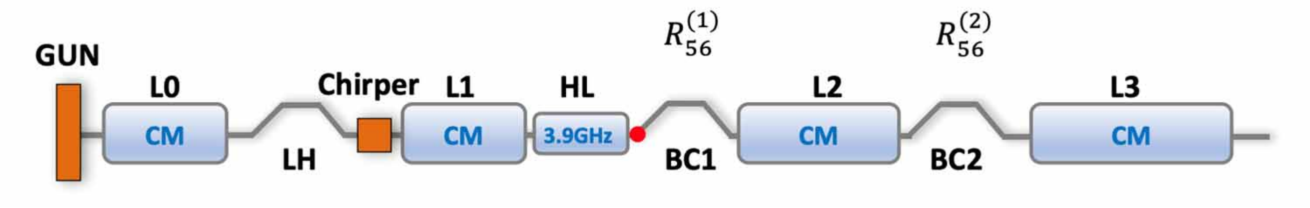
⇩

Beam on demand: provide tailored beam properties for each undulator line at the desired repetition rate, including *beam current, bunch length, beam shaping, beam charge, beam energy* …

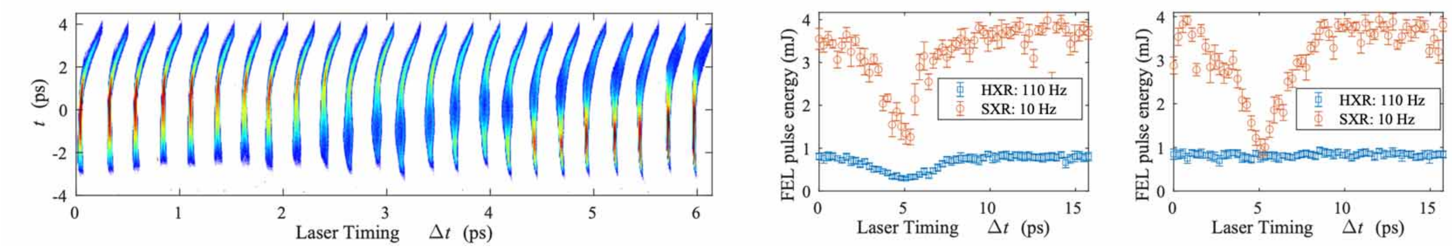
Beam on demand

Develop various methods for LCLS-II

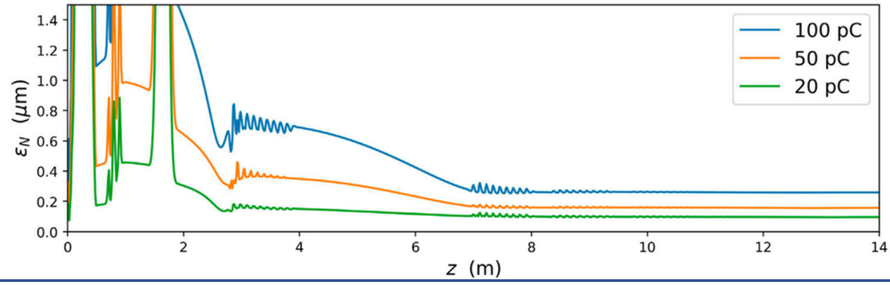
- Normal-conducting chirper cavity
  - *Peak current, bunch length*



- Selectively laser heater shaping
  - *Beam shaping, attosecond pulse*

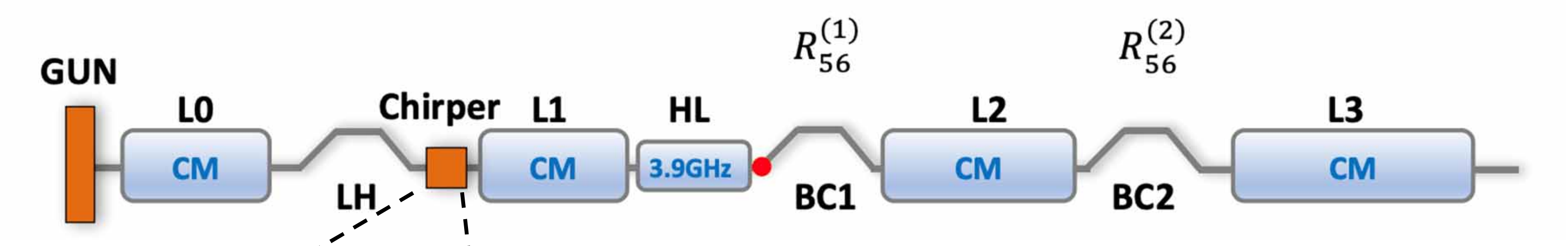


- Multiplexed injector configuration
  - *Beam charge*

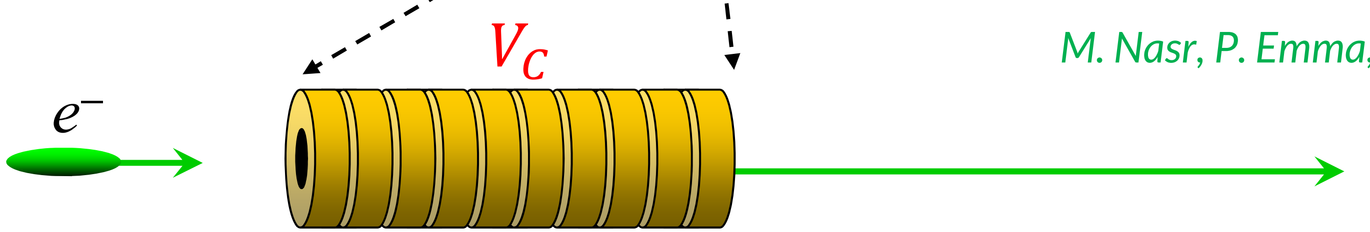


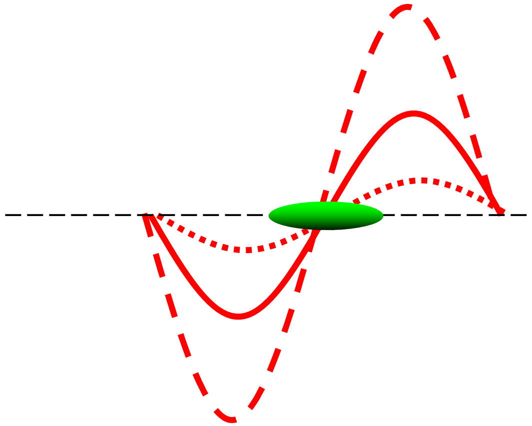
Normal-conducting chirper cavity

Shot-by-shot control of beam compression



M. Nasr, P. Emma, S. Tantawi, IPAC2016





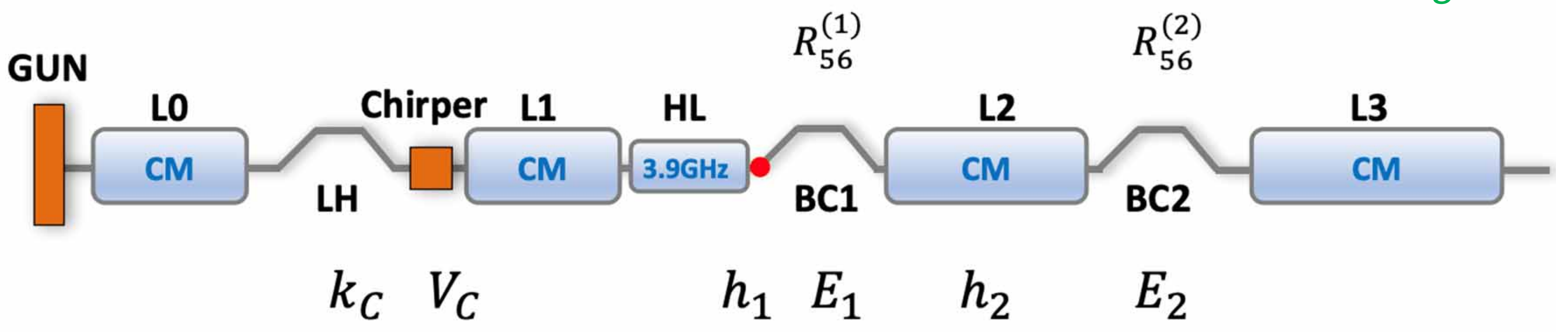
NC chirper cavity → CW mode → vary energy chirp shot-by-shot

- Fill time < bunch spacing
- Induced chirp $\propto \frac{V_c}{\lambda_c} \propto f_c \cdot V_c$
- Smaller aperture leads to less RF power

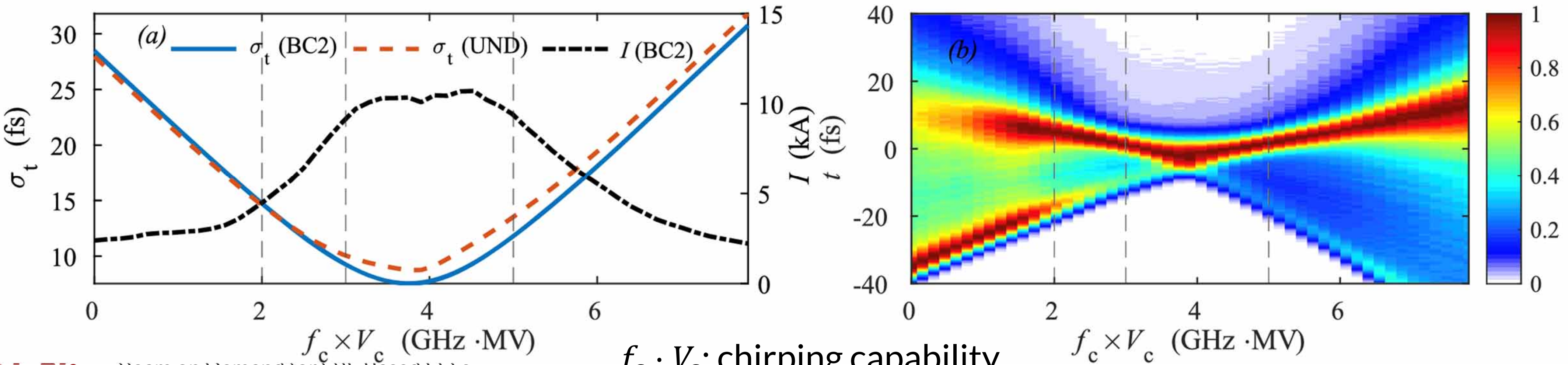
Normal-conducting chirper cavity

Shot-by-shot control of beam compression

M. Nasr, P. Emma, S. Tantawi, IPAC2016
Z. Zhang et al. RSI, 94, 024706 (2023)



Beam total compression factor: $C^*_{tot} \approx C_{tot} F_C,$ $\quad F_C = \dfrac{1}{1 - C_1 C_{tot} k_C \dfrac{eV_C \sin(\phi_C)}{E_2} R_{56}^{(2)}}.$



$f_c \cdot V_c$: chirping capability

Normal-conducting chirper cavity

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M. Nasr, P. Emma, S. Tantawi, IPAC2016
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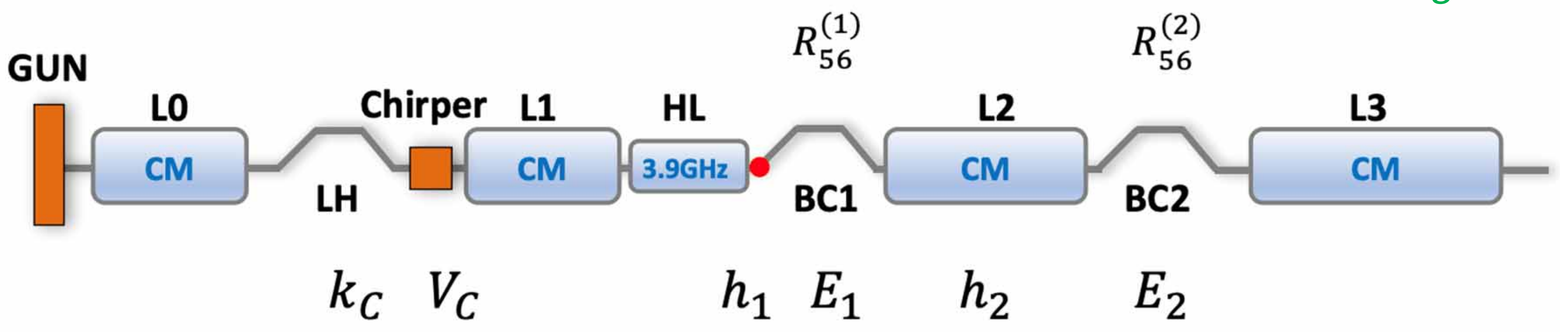

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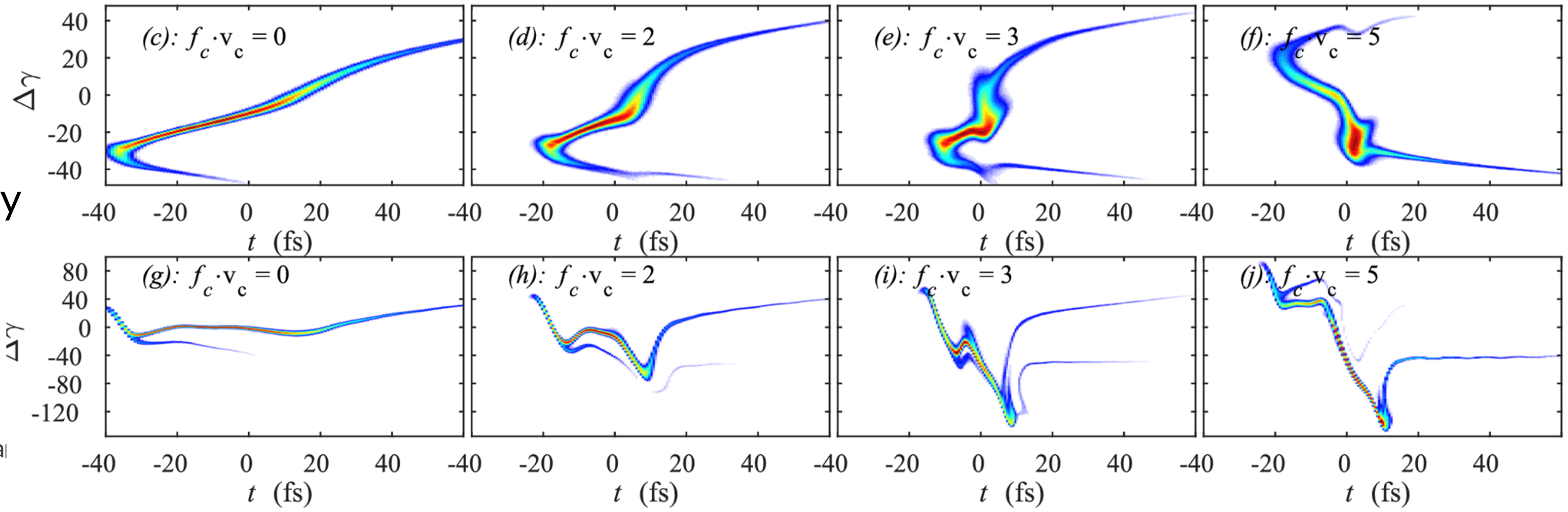
$f_c \cdot V_c$: chirping capability



Normal-conducting chirper cavity

Cavity RF design

- Preliminary RF design for different RF frequencies (3.9/7.8/11.7 GHz), iris radius (6/8/10 mm) and cavity types.
- Keep the chirping capability for all designs

$$f_C[GHz] \cdot V_c[MV] = 5$$

- Higher frequency leads to smaller RF power and shorter fill time.
- However, no commercial SSA sources available at high frequency (7.8/11.7 GHz) .
- 3.9 GHz is the primary option since it needs a similar SSA with the harmonic linearizer that is already in the LCLS-II accelerator

Z. Zhang et al. RSI, 94, 024706 (2023)

TABLE III. RF parameters of accelerating structures for LCLS-II-HE chirper.

RF frequency (GHz)	Cavity voltage (keV)	Iris radius (mm)	Circuit type	Input RF power (kW)	Filling time (ns)	Shunt impedance (MΩ/m)	a/λ	Q_0
3.9	1282	6	Single pass	12.4	1000	83.5	0.078	12 746
		8	Single pass	16.0	1000	63.7	0.104	11 684
		10	Single pass	20.2	1000	50.0	0.130	10 471
		10	Resonant ring	12.0	696	69.3	0.130	12 909
7.8	641	6	Single pass	3.95	391	63.8	0.156	7 606
		8	Single pass	10.8	273	23.3	0.208	5 313
		8	Resonant ring	3.42	344	60.3	0.208	9 267
		10	Resonant ring	4.59	325	44.8	0.260	9 540
11.7	427	6	Single pass	3.87	160	29.0	0.234	4 568
		6	Resonant ring	1.50	178	61.1	0.234	7 576
		8	Resonant ring	2.27	184	40.3	0.312	7 984
		10	Resonant ring	3.33	204	27.2	0.390	8 591

E. Snively and V. Dolgashev

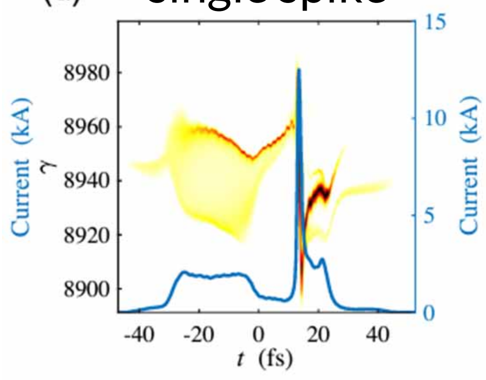
Laser heater shaping

Laser heater shaping can be used for …

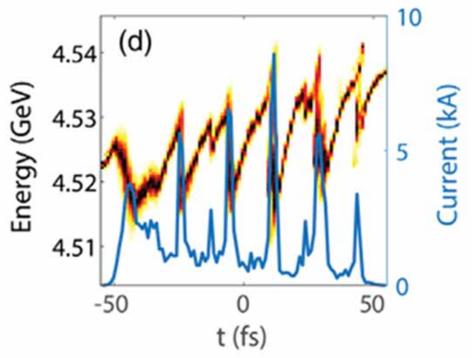
- Single ultrashort spike for attosecond generation
- Pulse stacking / pulse train
- Current horn suppression
- Frequency beating
- Selective FEL lasing

D. Cesar et al., PRAB 24, 110703 (2021)

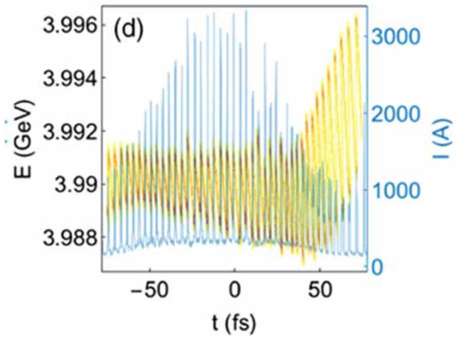
single spike



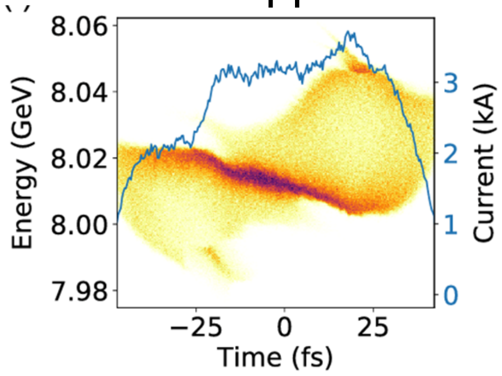
Pulse stacking

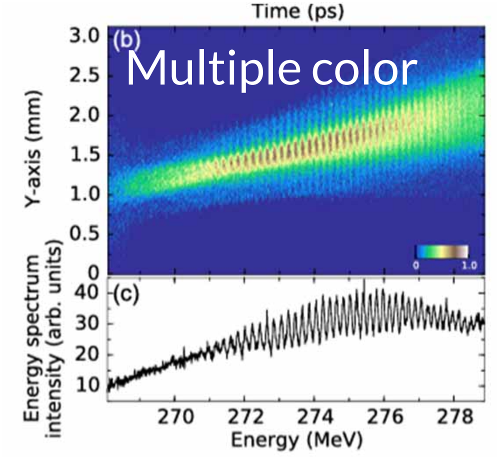


Pulse train

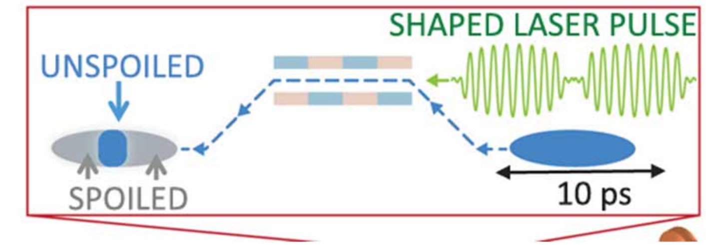


Horn suppression





Selective FEL lasing

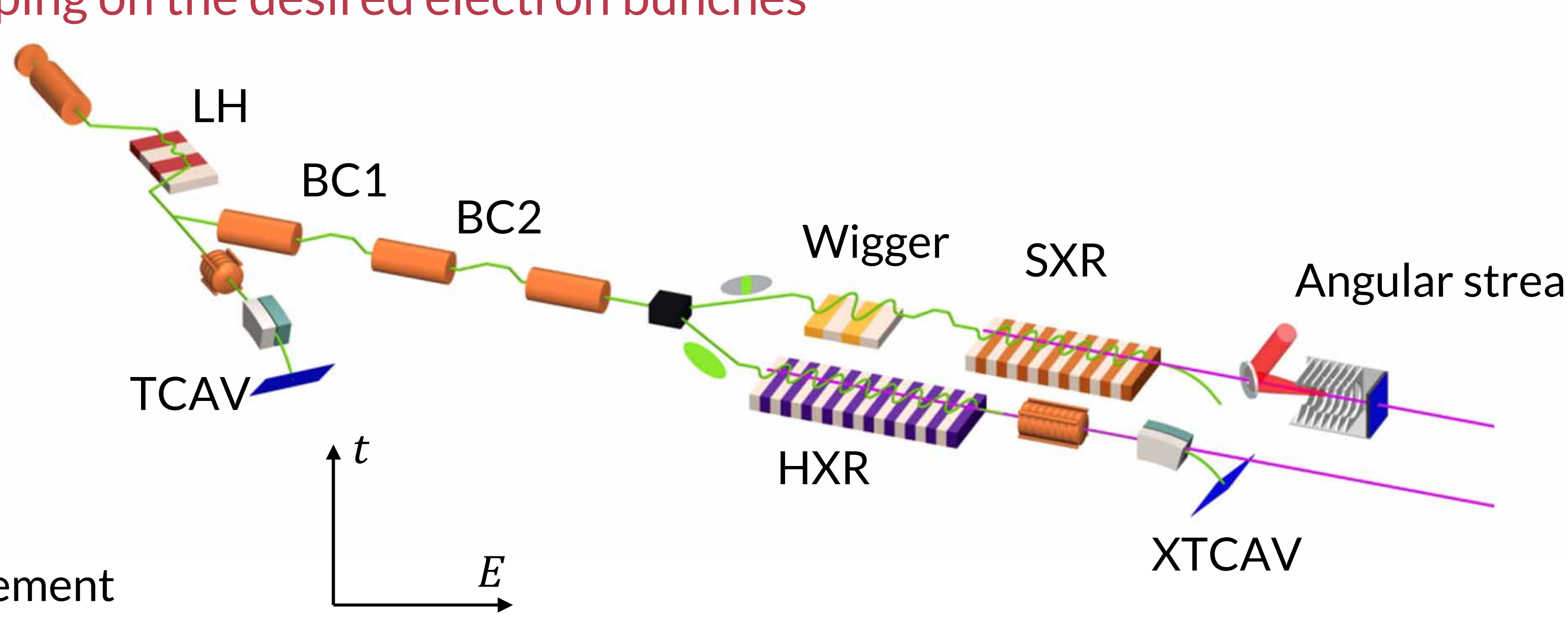


A. Marinelli et al., PRL 116, 254801 (2016)

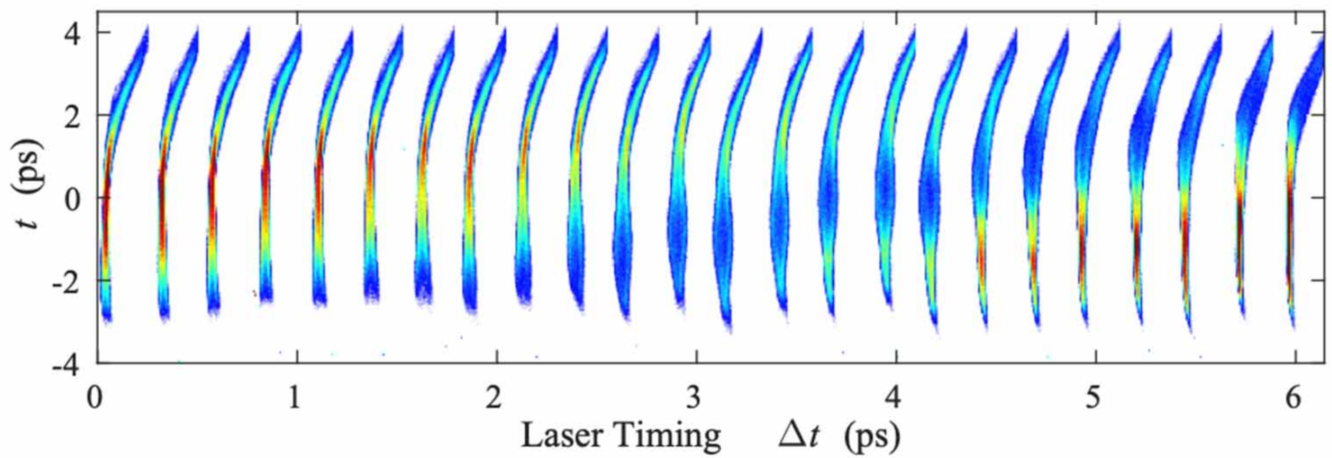
E. Roussel et al., PRL 115, 214801 (2015)

Selective laser heater shaping

Apply shaping on the desired electron bunches



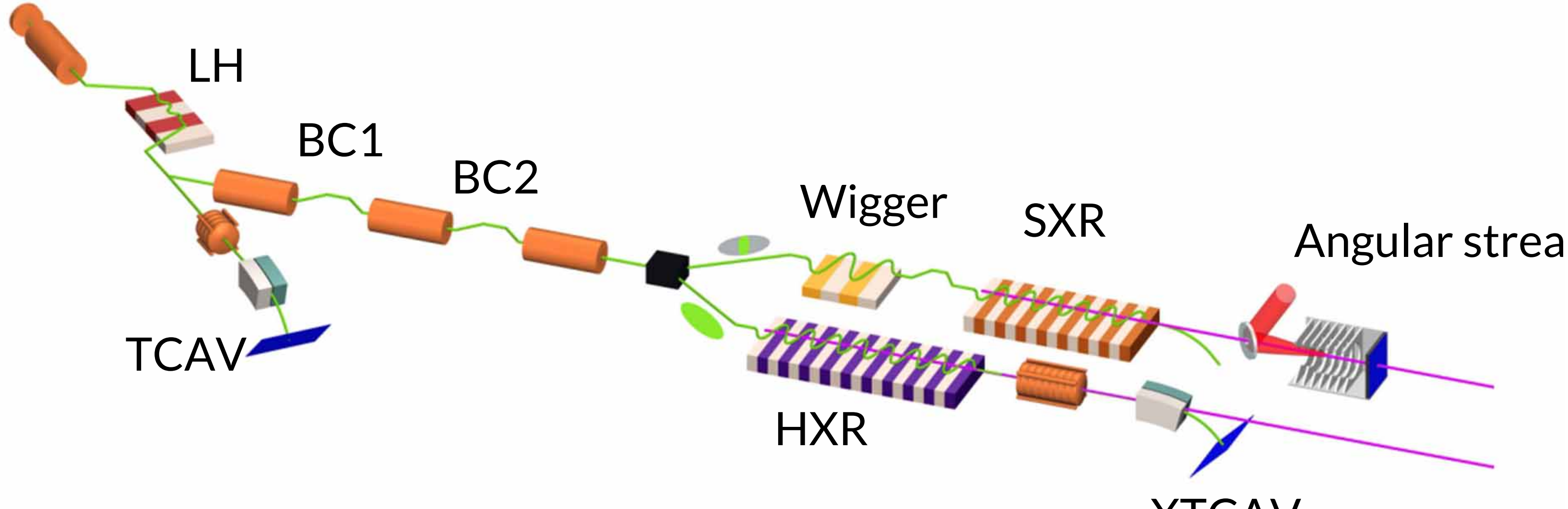
TCAV measurement

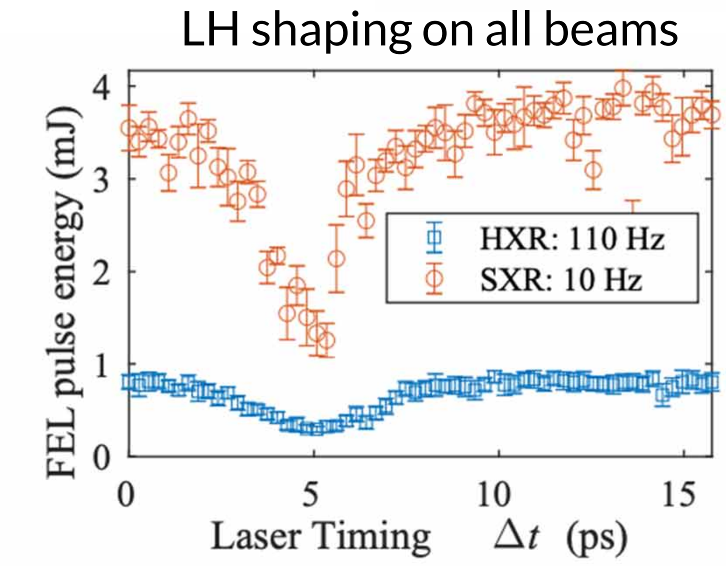


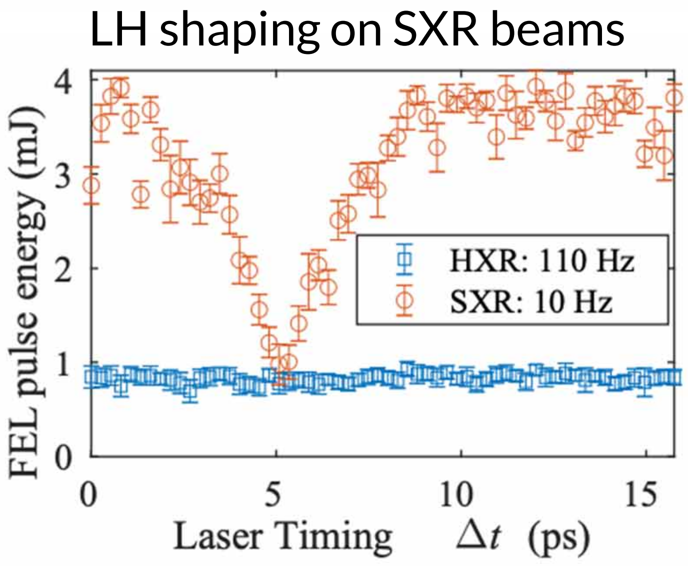
Paper in preparation

Selective laser heater shaping

Apply shaping on the desired electron bunches







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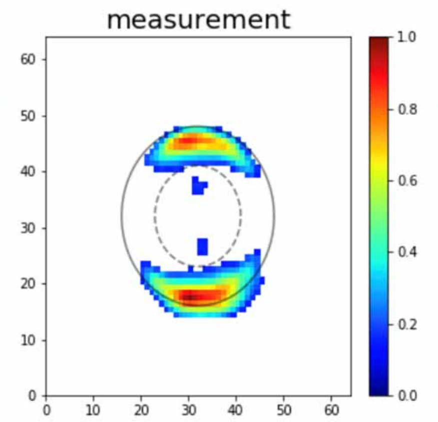
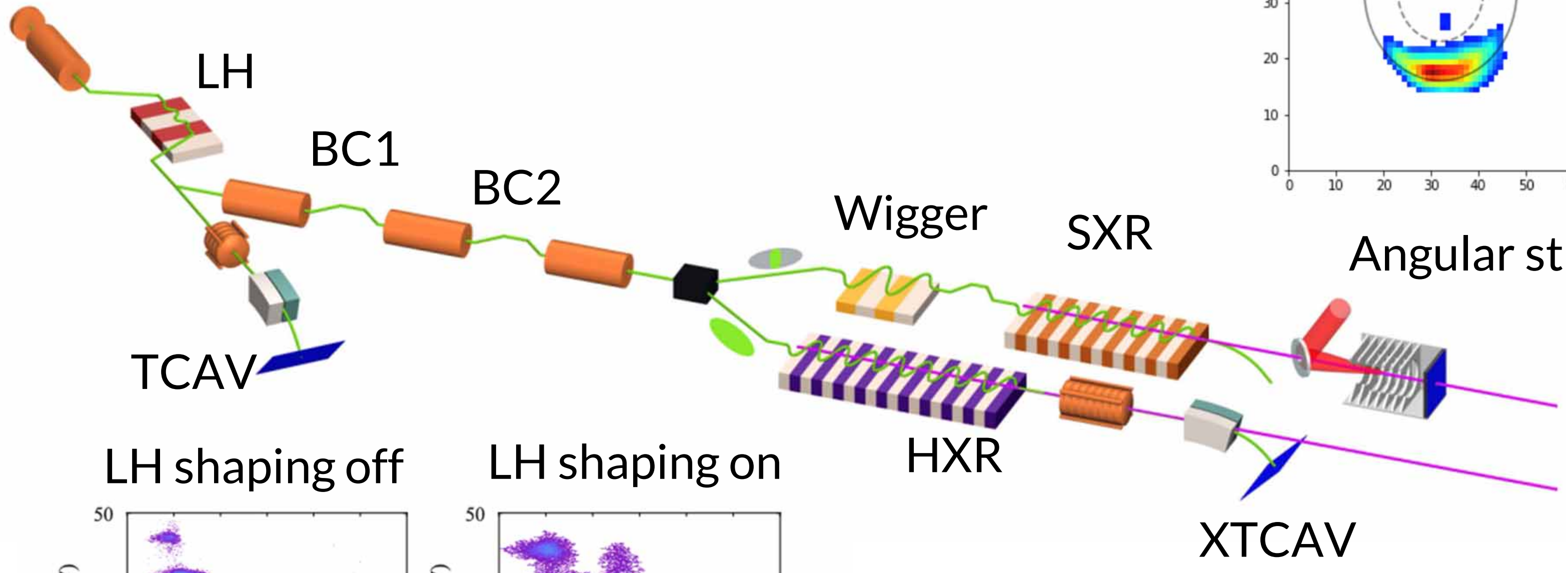
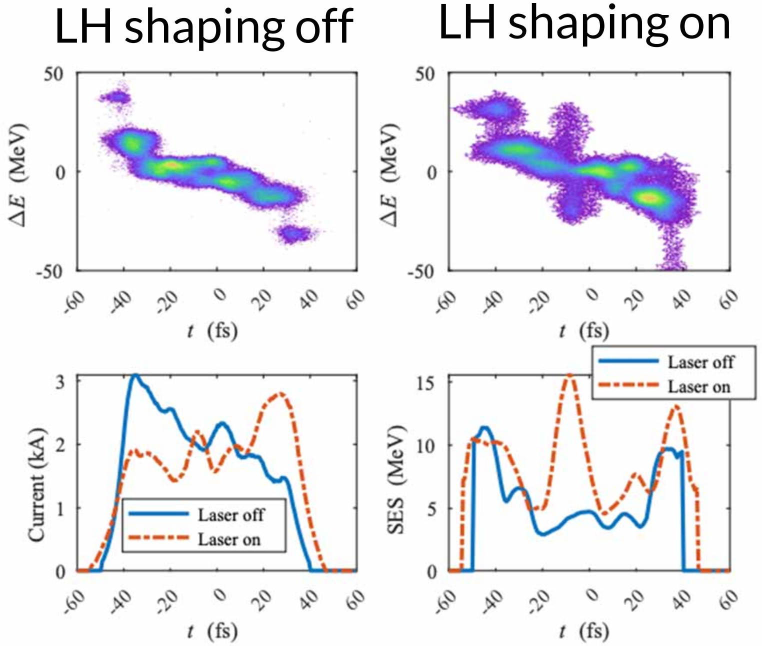


From S. Li

X-ray pulse duration ~400 as





Single spike for attosecond pulse

XTCAV measurement

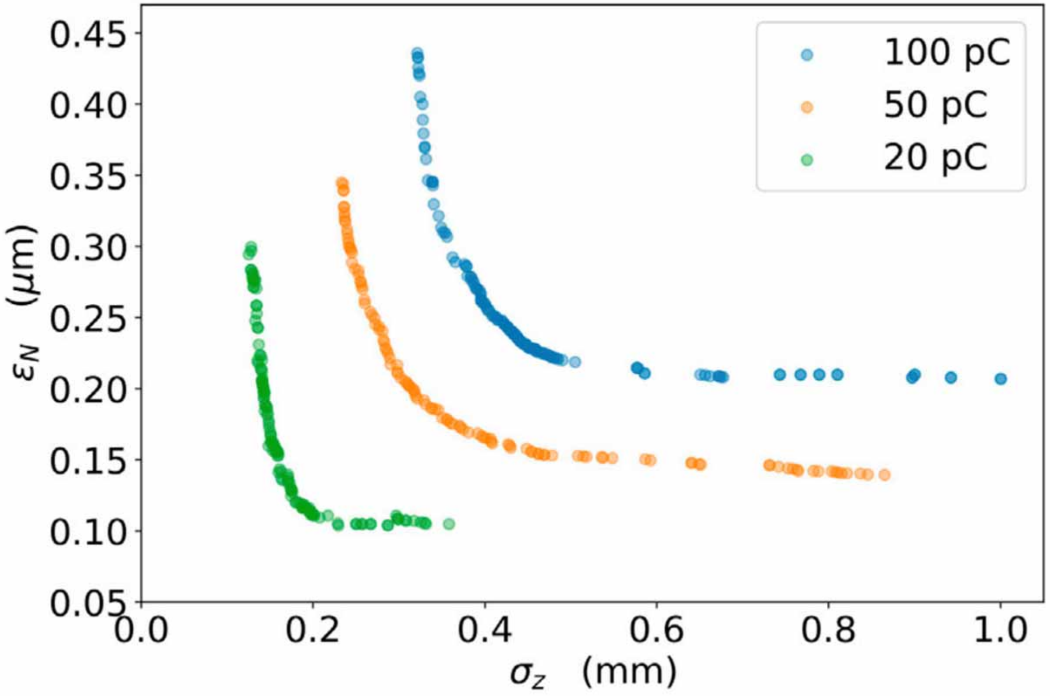
Paper in preparation

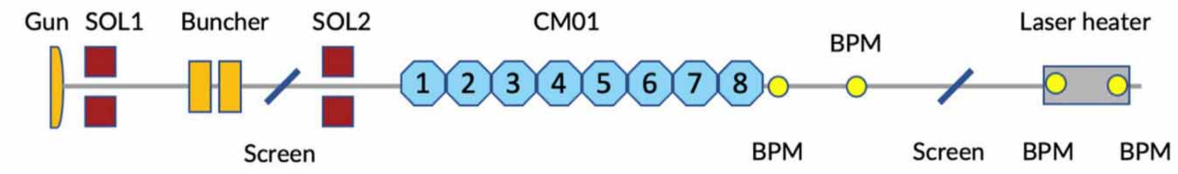
Multiplexed injector configuration

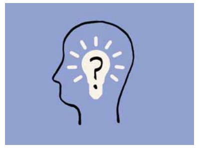
Produce low-emittance electron beams of different beam charges

- Injector settings are usually optimized for a given beam charge (100 pC, 50 pC and 20 pC for LCLS-II)
- Explore the possibility to deliver multiple beam charges from the LCLS-II injector

Optimization for single charge







Optimization assumptions:

Shared parameters: all magnet and RF settings

Tunable parameters: mainly from the drive laser, e.g., laser arrive time, laser pulse duration and laser spot size

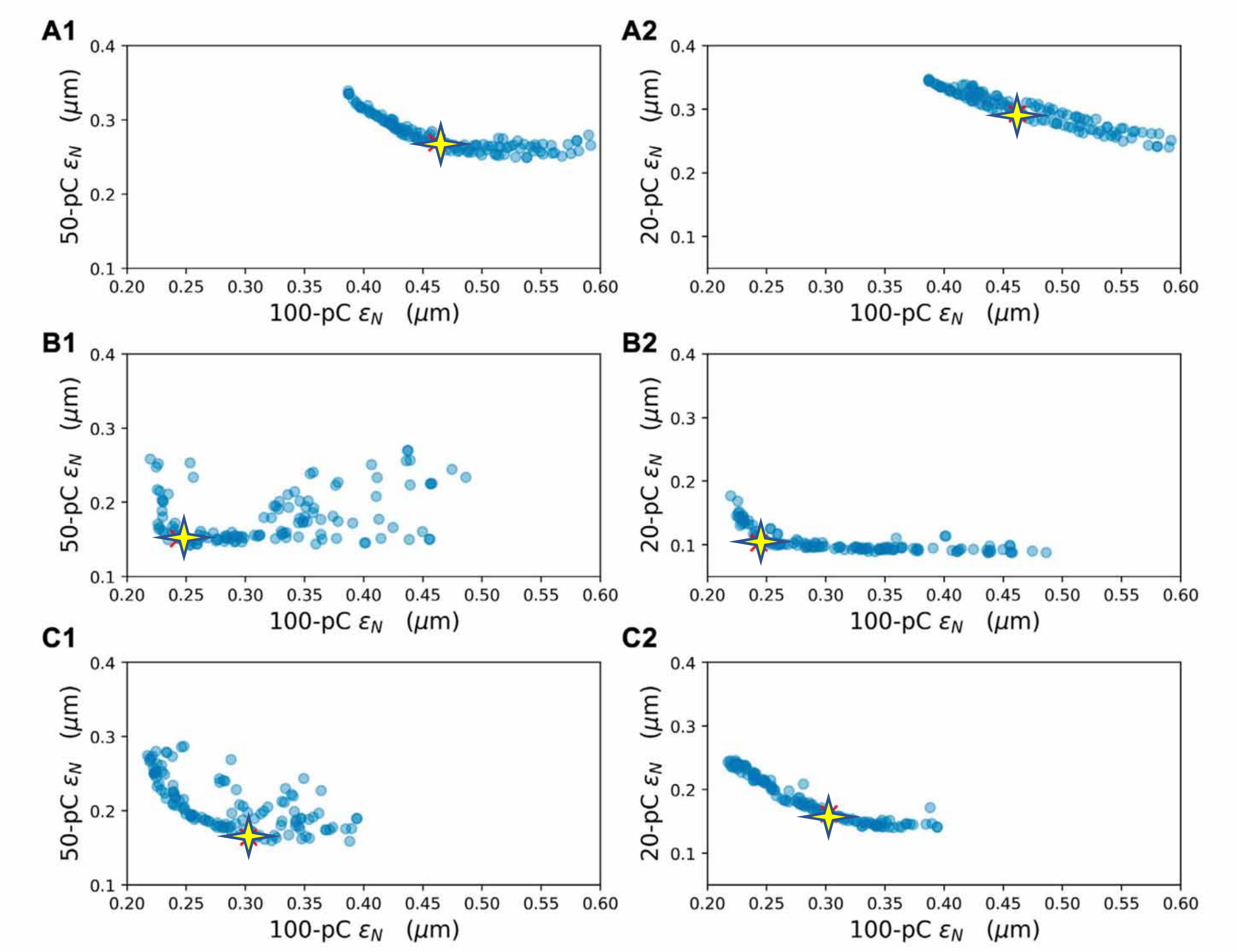
Multiplexed injector configuration

Optimization results

Z. Zhang et al., Frontiers in Physics, 11, 249 (2023)

- Bunch length
  - 100 pC: 1.0 mm
  - 50 pC: 0.8 mm
  - 20 pC: 0.6 mm

- A: no tunable parameters for different charges
- B: customized laser spot size for each charge
- C: customized laser pulse duration for each charge



Multiplexed injector configuration

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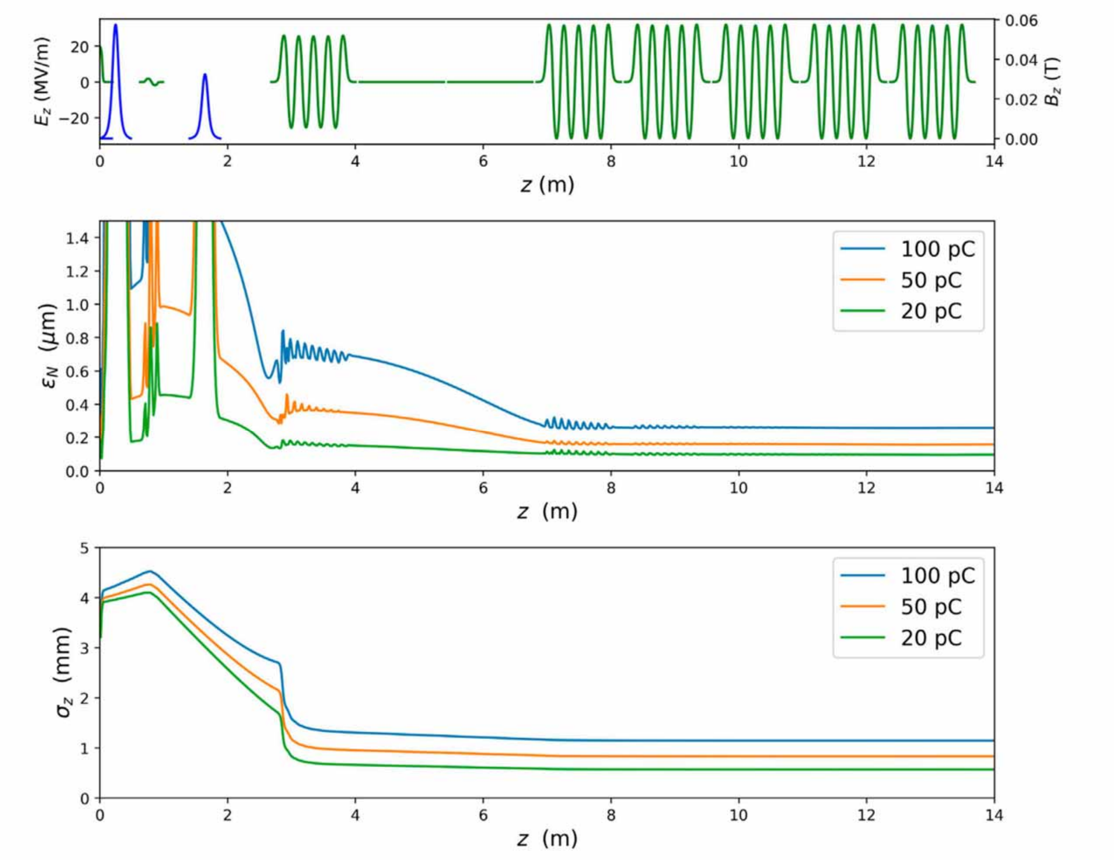
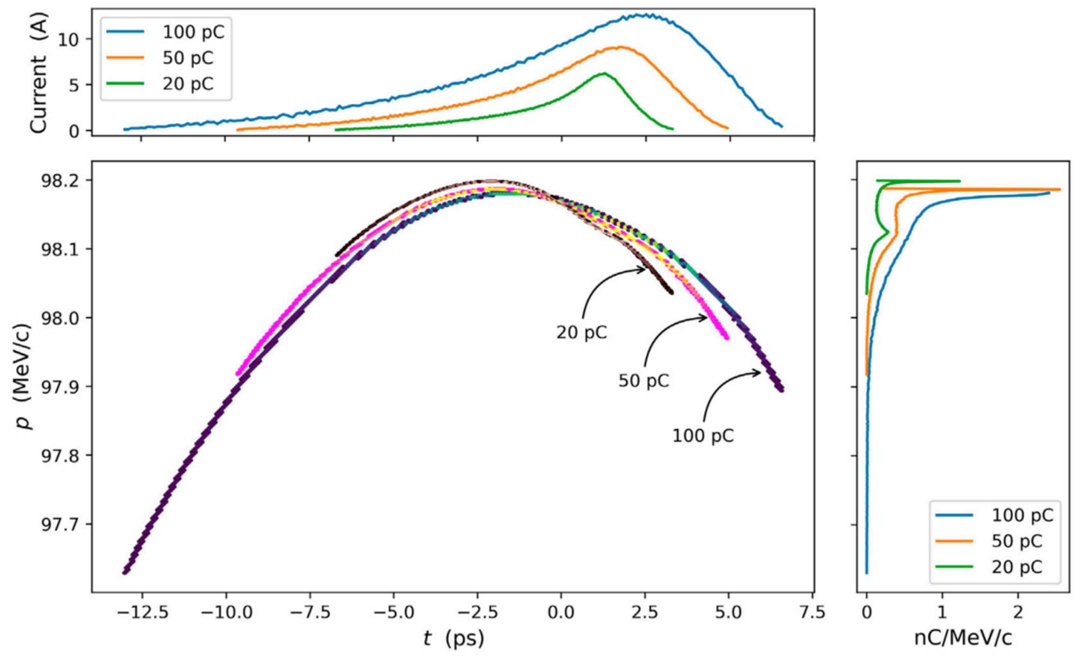
Parameter	Unit	Baseline	Case A	Case B	Case C
100-pC σ_z	mm	1.00	1.08	1.10	1.06
50-pC σ_z	mm	0.80	0.87	0.80	0.83
20-pC σ_z	mm	0.60	0.58	0.55	0.69
100-pC ϵ_n	μm	0.20	0.46	0.24	0.30
50-pC ϵ_n	μm	0.15	0.27	0.15	0.16
20-pC ϵ_n	μm	0.10	0.29	0.10	0.16
sum of ϵ_n	μm	0.45	1.02	0.49	0.62

Multiplexed injector configuration

Deliver low-emittance beam beams with three charges





Summary

Beam on Demand

- The wide-ranging requirements for the photon properties from multiple undulator lines demand more challenging beam manipulation techniques.

- **Beam compression, peak current and bunch length** → normal-conducting chirper cavity in CW mode
- **Beam shaping, current profile, special features** → selective laser heater shaping
- **Beam charge** → multiplexed injector configuration
- More to be explored …

- Thanks for the funding support from DOE BES - Accelerator and Detector Research.
- Thanks for your attention.