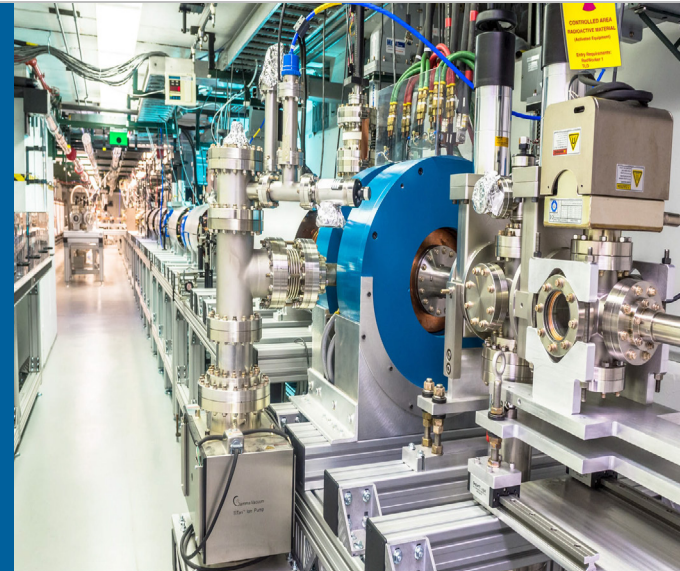


2022/08/12 NAPAC2022, ALBUQUERQUE, FRXD2



EXPERIMENTAL DEMONSTRATION OF MULTIFUNCTIONAL LONGITUDINAL BEAM PHASE-SPACE MANIPULATION PLATFORM VIA DOUBLE EMITTANCE-EXCHANGE



JIMIN SEOK¹, MOSES CHUNG¹

GWANGHUI HA², JOHN POWER², MANOEL CONDE², WANMING LIU², ERIC WISNIEWSKI²,
CHARLES WHITEFORD²

1. UNIST 2. ANL



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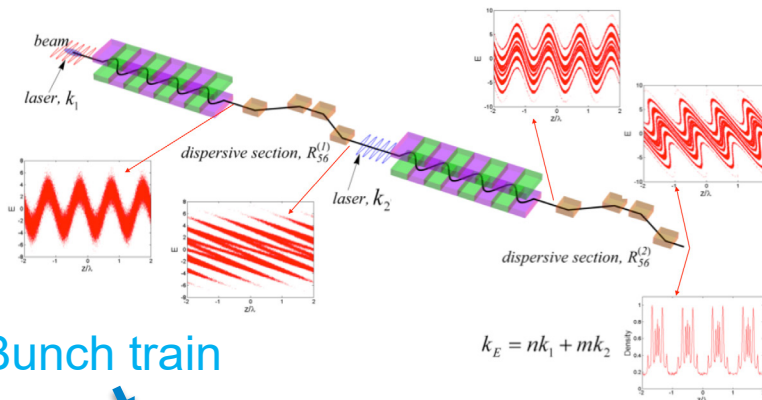
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OUTLINE

- **Introduction**
 - Why do we need longitudinal phase space manipulation?
 - Existing longitudinal manipulation methods
- **Double Emittance-EXchange concept**
 - Why DEEX? and DEEX's strong points
 - Experimental demonstrations of key longitudinal manipulations
- **Exemplified applications**
- **Summary**

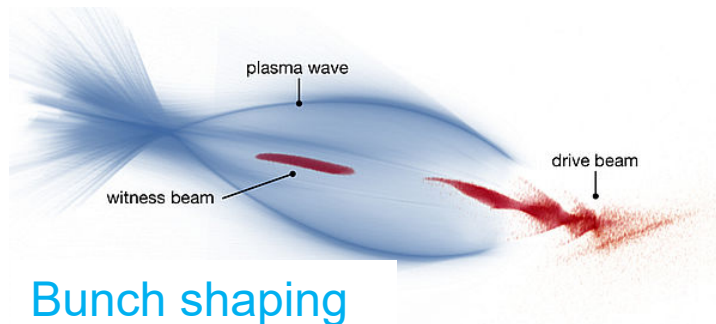
WHY DO WE NEED LONGITUDINAL MANIPULATION?



Bunch train

Echo-Enabled Harmonic Generation

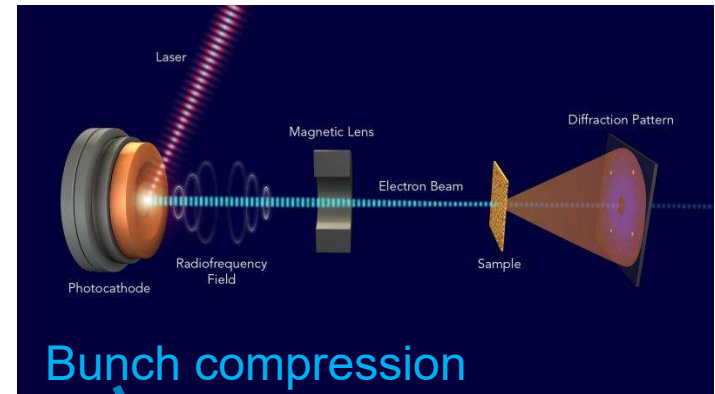
Ref. https://portal.slac.stanford.edu/sites/ard_public/tfd/facilities/nlcta/Pages/Echo-enabled-Harmonic-Generation.aspx



Bunch shaping

Beam-driven plasma wakefield acceleration

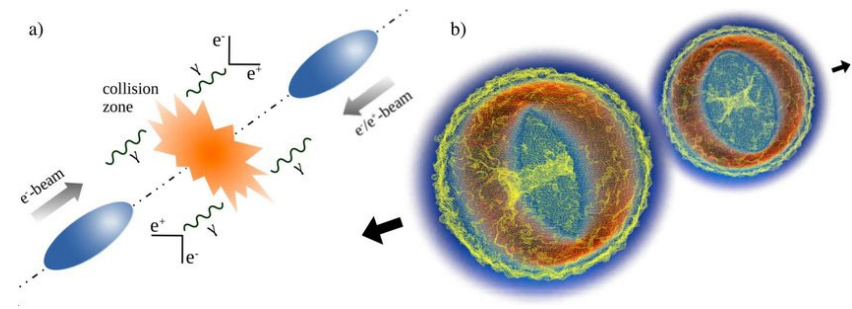
Ref. <https://www.gauss-center.de/results/elementaryparticlephysics/article/electron-injection-techniques-in-plasma-wakefield-accelerators-for-driving-free-electron-lasers/>



Bunch compression

Ultrafast Electron Diffraction

Ref. <https://phys.org/news/2015-08-ultrafast-electron-diffraction-reveals-rapid.html>



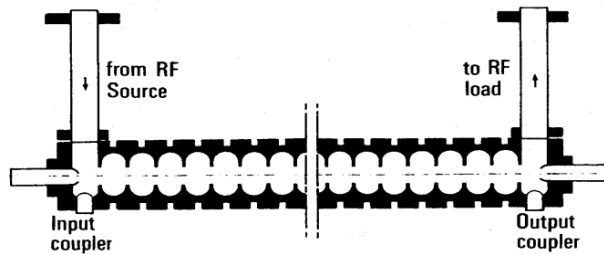
Bunch compression

Beam-Beam collider

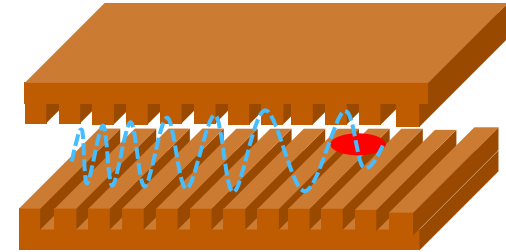
Ref. V. Yakimenko, *et al.*, PRL 122, 190404 (2019)

EXISTING LONGITUDINAL MANIPULATIONS

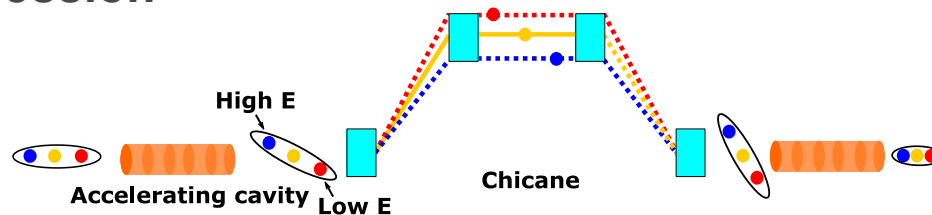
- Energy manipulation



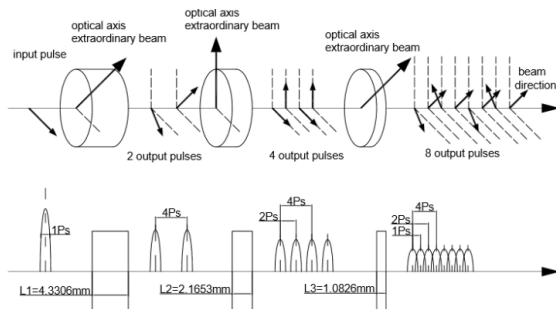
Ref. Nicolas Pichoff, Introduction to RF linear accelerators



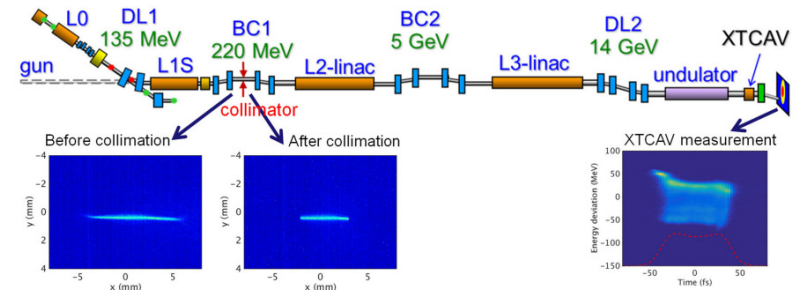
- Bunch compression



- Current profile shaping



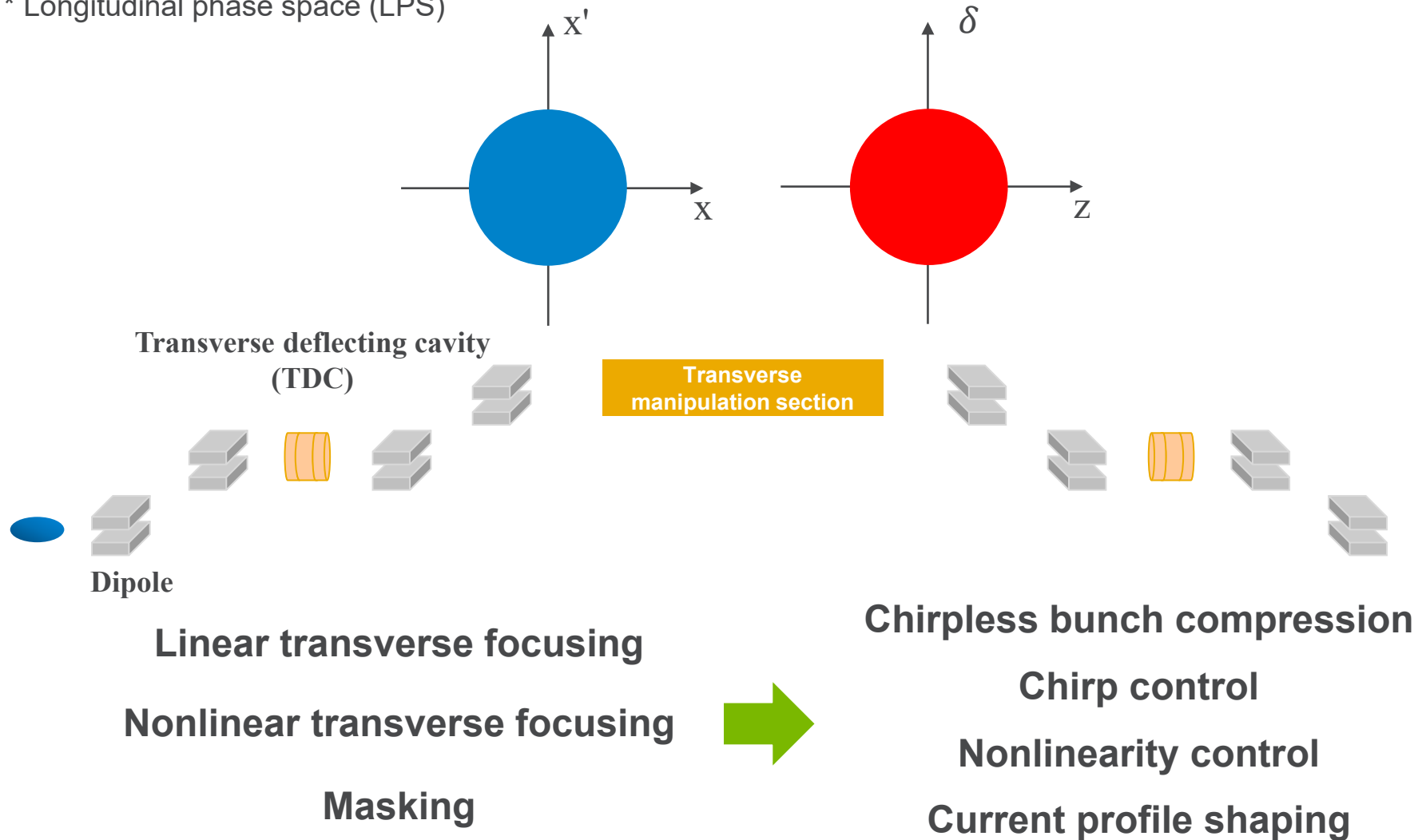
Ref. C. Lie, *et. al*, FEL2019, WEP058



Ref. Y. Ding, *et. al*, PRAB 19, 100703 (2016)

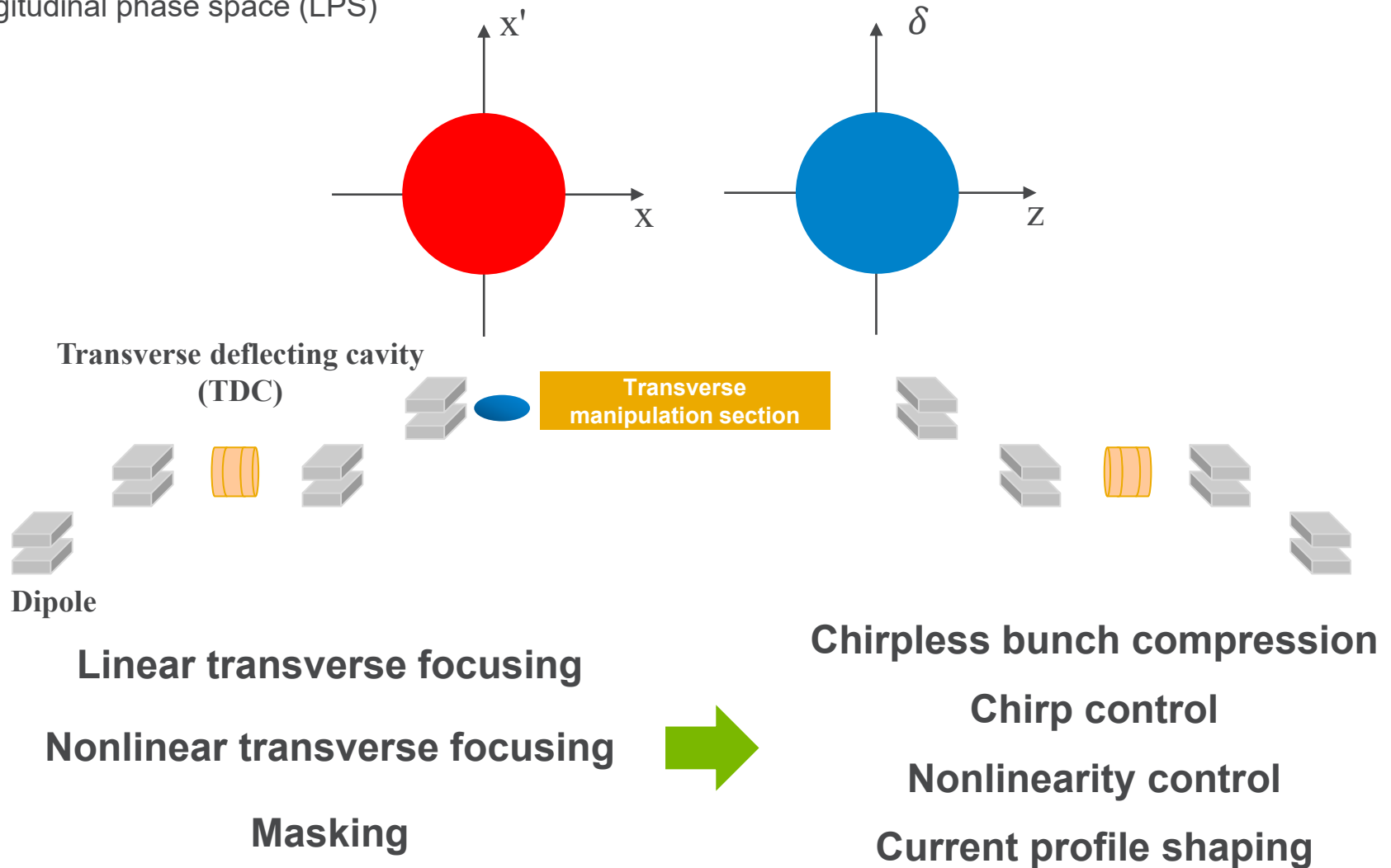
LPS MANIPULATION PLATFORM: DOUBLE EMITTANCE-EXCHANGE

* Longitudinal phase space (LPS)



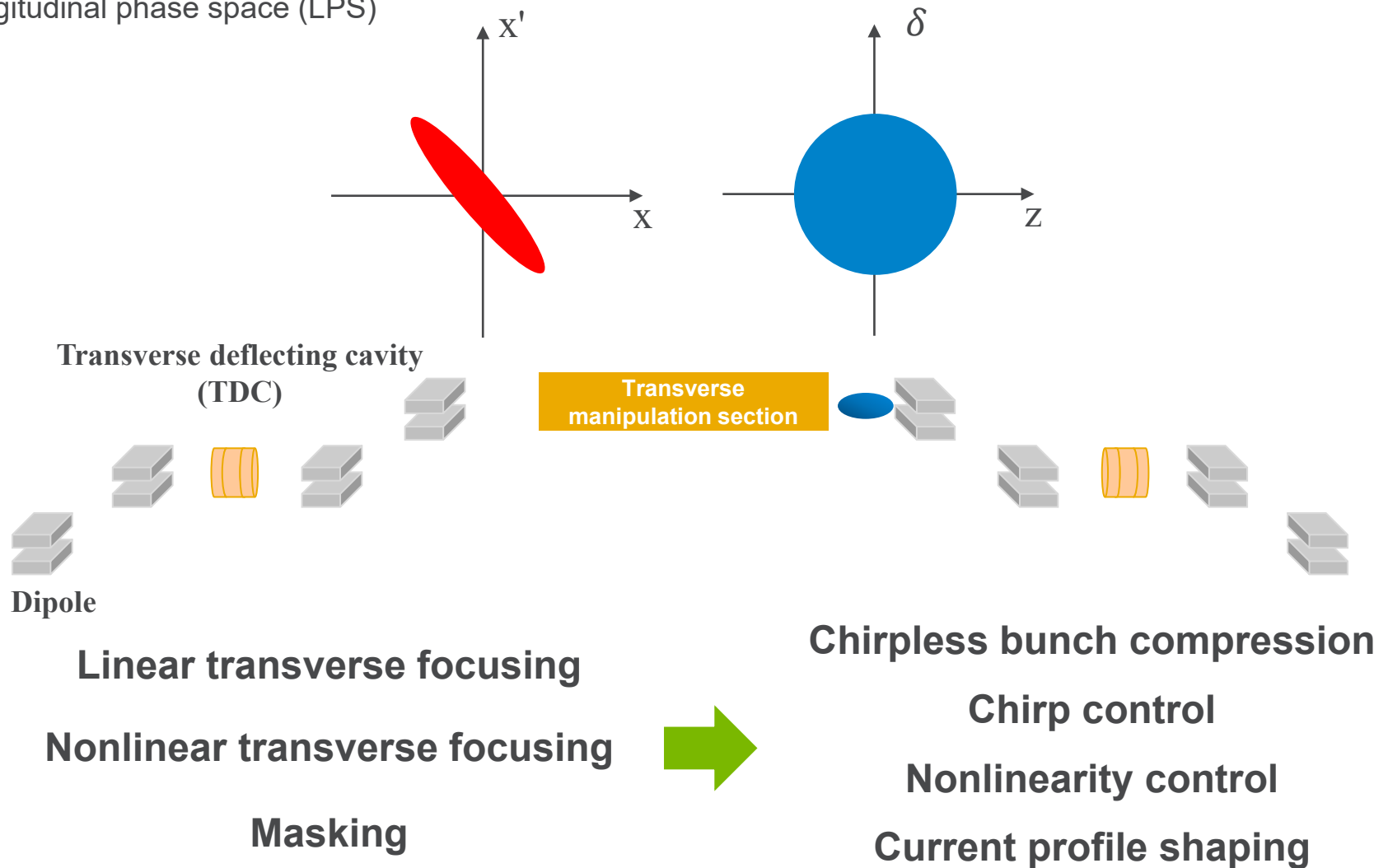
LPS MANIPULATION PLATFORM: DOUBLE EMITTANCE-EXCHANGE

* Longitudinal phase space (LPS)



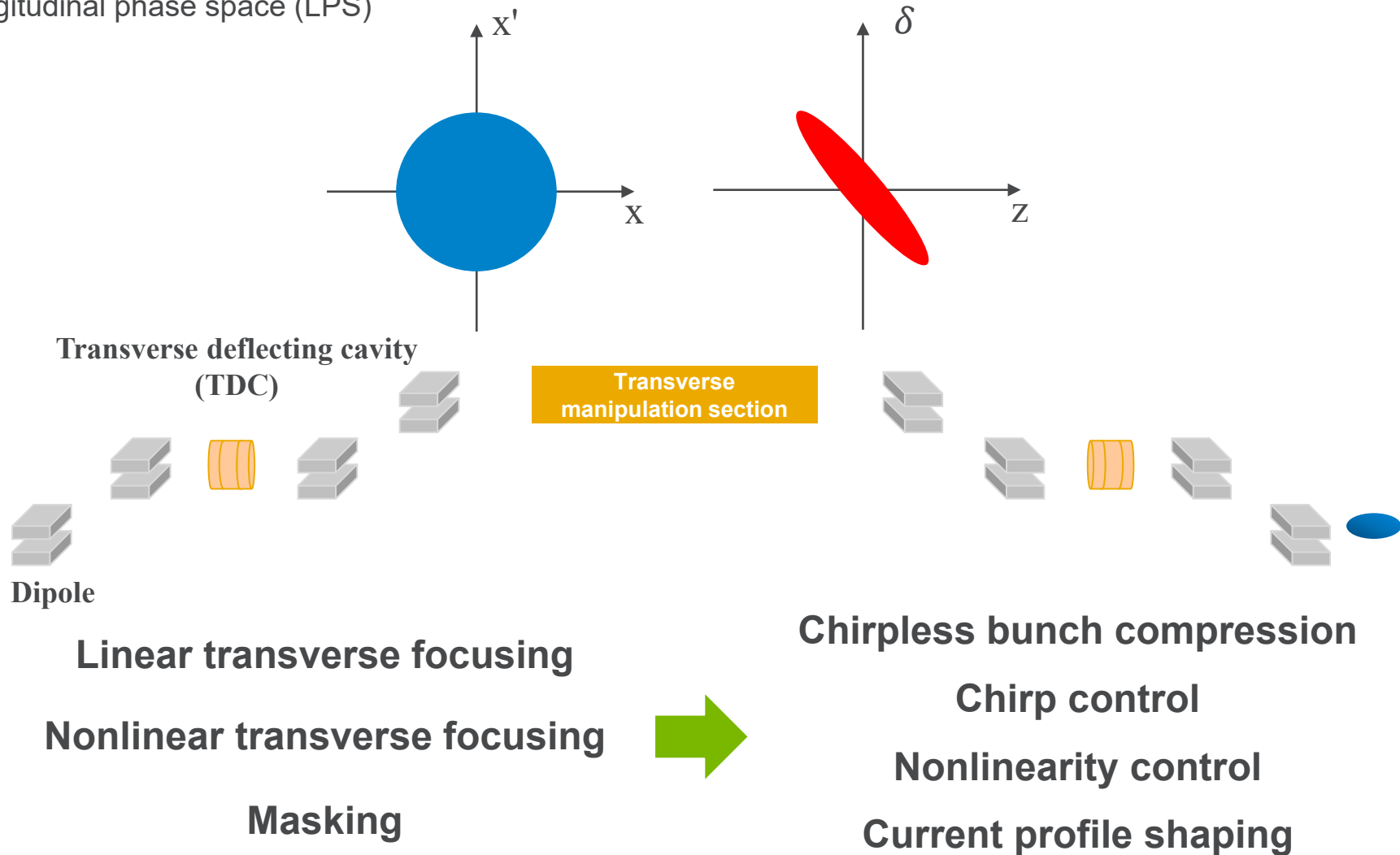
LPS MANIPULATION PLATFORM: DOUBLE EMITTANCE-EXCHANGE

* Longitudinal phase space (LPS)



LPS MANIPULATION PLATFORM: DOUBLE EMITTANCE-EXCHANGE

* Longitudinal phase space (LPS)



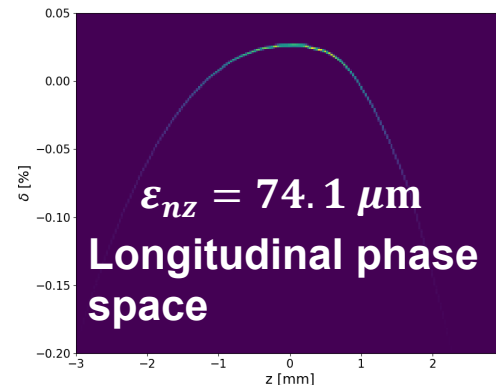
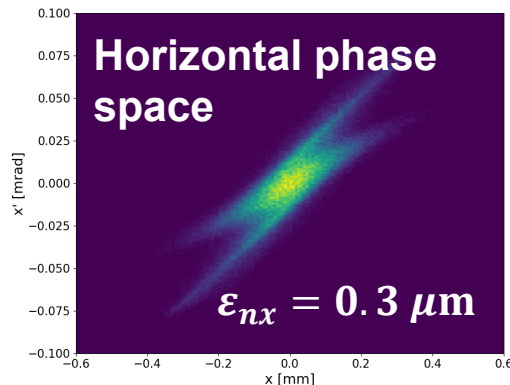
DEEX'S STRONG POINTS

- **Efficient use of RF power**
 - All accelerating cavities can be operated at the on-crest phase
- **Cheap nonlinear time-energy correlation control**
 - Manipulations by nonlinear magnets
 - No need of extra high frequency power sources
- **Arbitrary current profile**
 - Combination of transverse magnets and masks allow precise shaping of the current profile

All above can be accomplished simultaneously!

WHY DOUBLE?

- **Exchange of emittances**
 - Initially large longitudinal emittance results in a large transverse emittance.



Example: LCLS-II injector

*The simulation input files were achieved from <https://www.slac.stanford.edu/grp/ad/model/lcls2.html>

- **Timing and energy jitters**
 - All timing and energy jitters become transverse jitters.

DEMONSTRATION OF LONGITUDINAL MANIPULATION VIA DOUBLE EMITTANCE-EXCHANGE

Chirpless bunch compression

Chirp control

Nonlinearity control

Not demonstrated yet

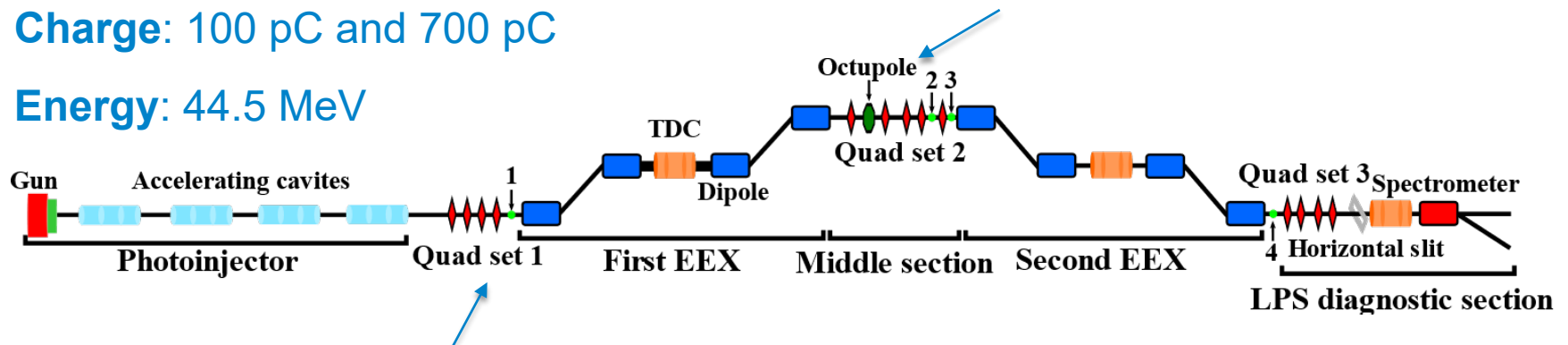
Current profile shaping

Demonstrated using single EEX

Transverse manipulation for longitudinal manipulation

Charge: 100 pC and 700 pC

Energy: 44.5 MeV

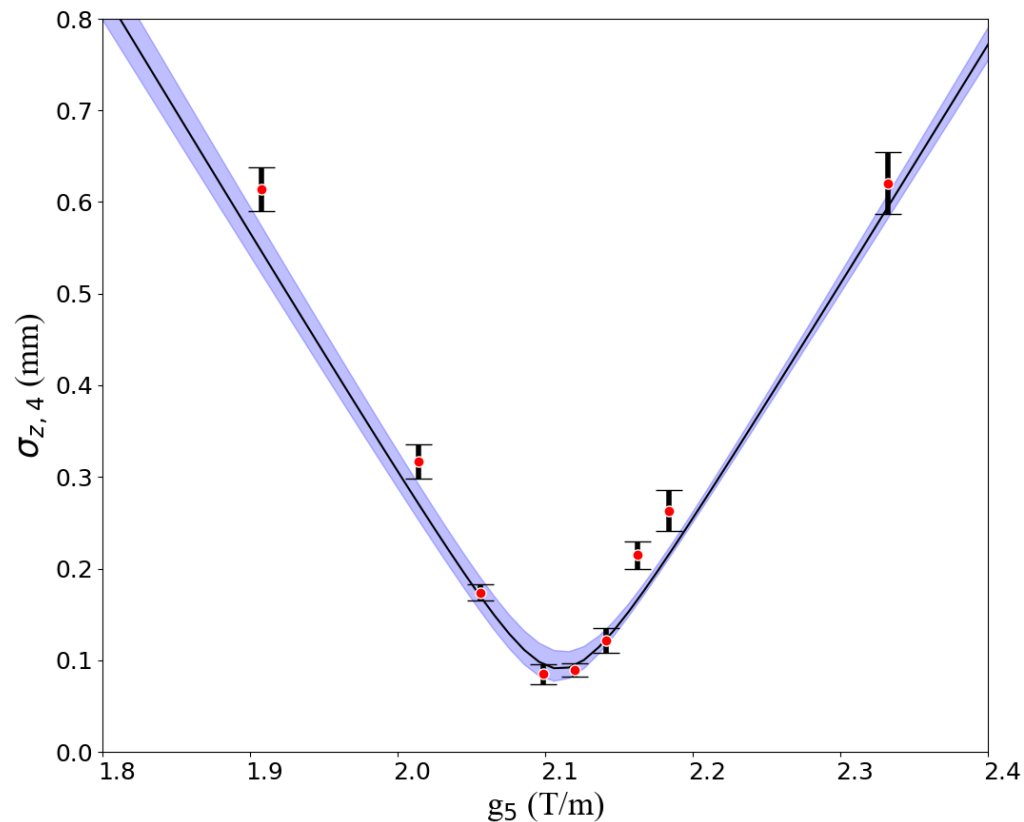
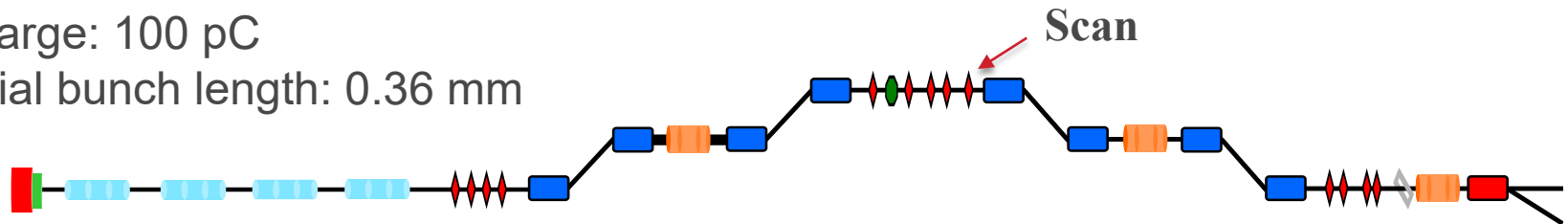


Matching for DEEX beamline

TUNABLE CHIRPLESS BUNCH COMPRESSION

Charge: 100 pC

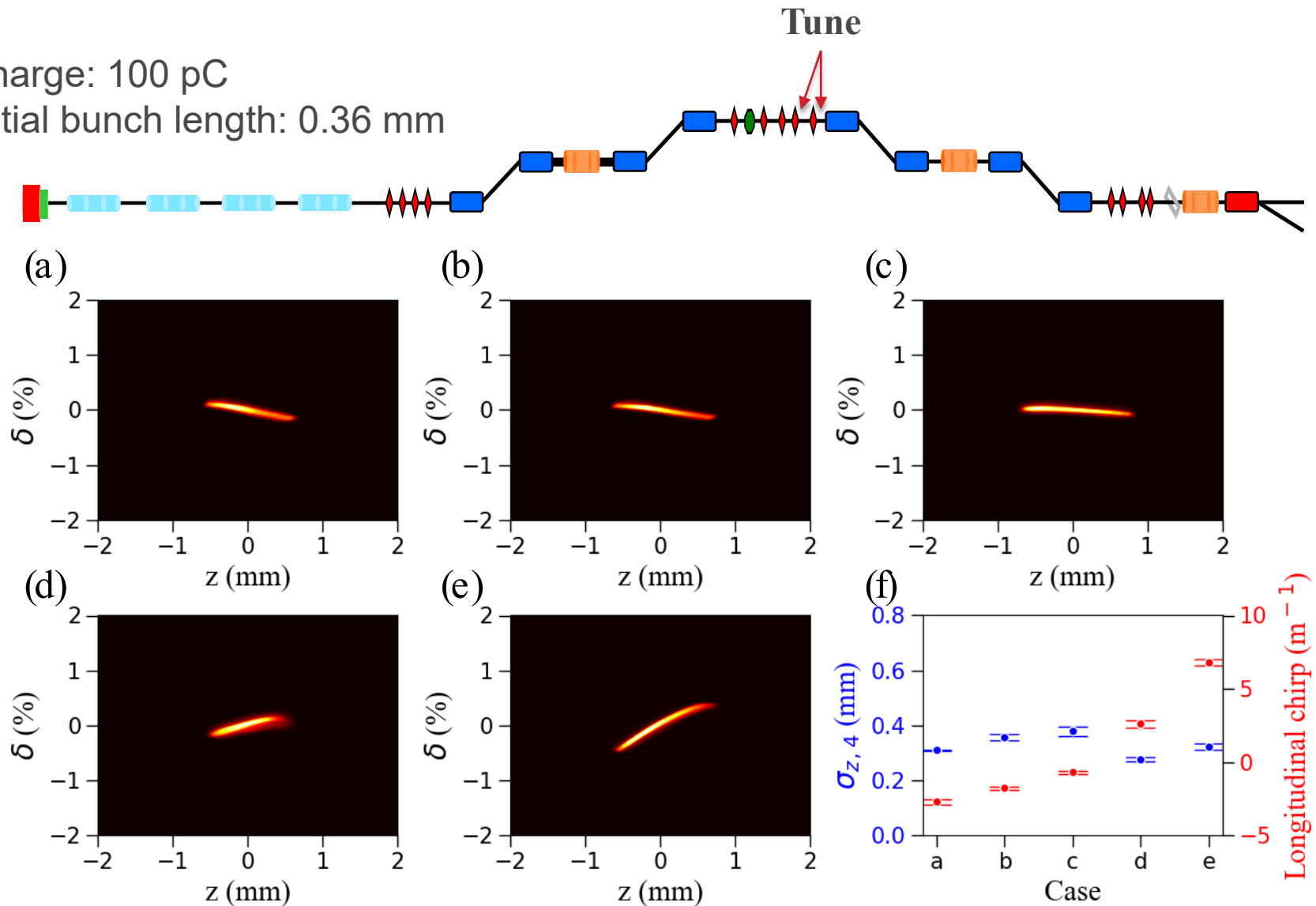
Initial bunch length: 0.36 mm



TUNABLE LONGITUDINAL CHIRP CONTROL

Charge: 100 pC

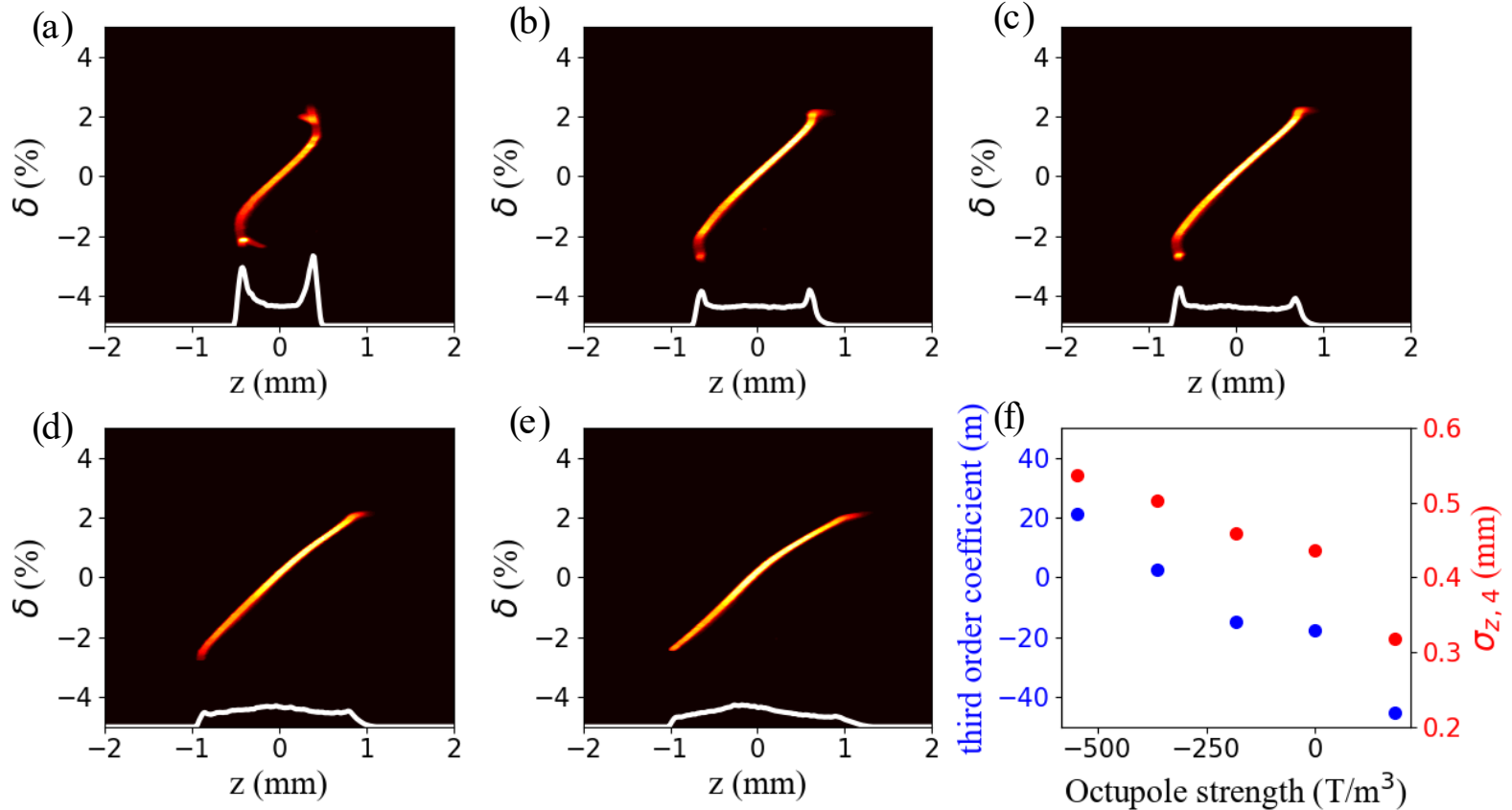
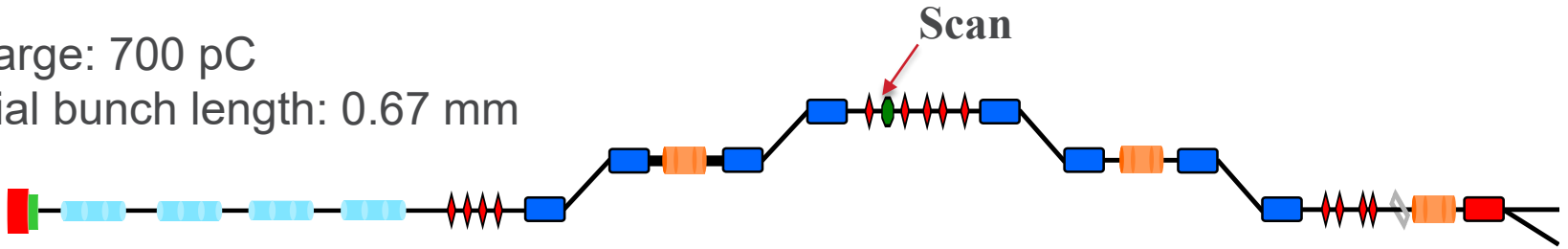
Initial bunch length: 0.36 mm



NONLINEARITY CONTROL

Charge: 700 pC

Initial bunch length: 0.67 mm



TWO EXAMPLED APPLICATIONS

- **Extremely low energy spread**
- **Multicolor radiation**

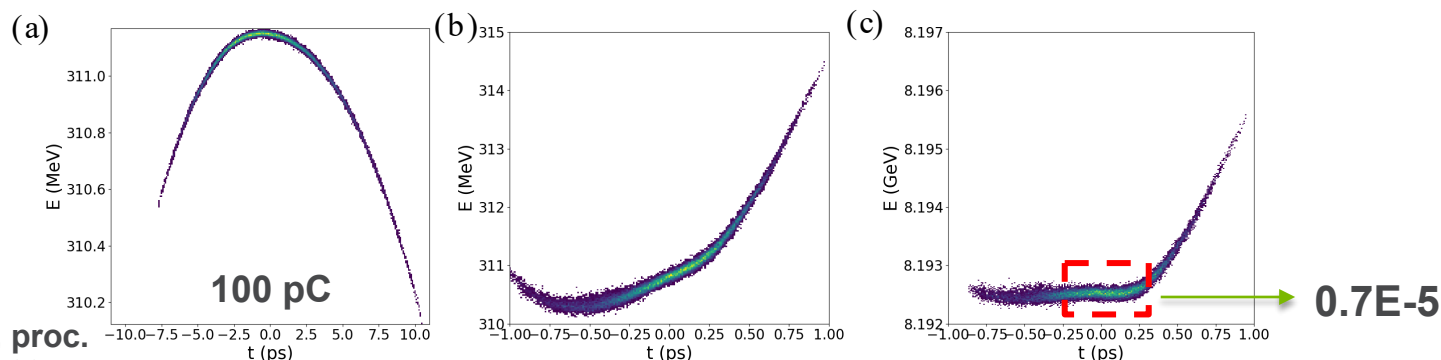
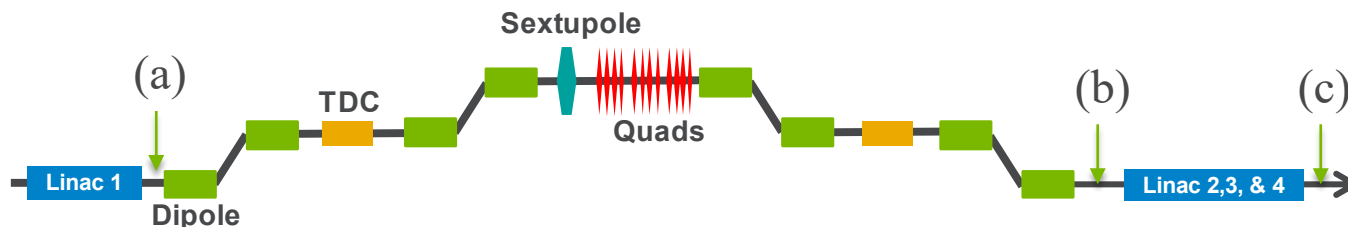


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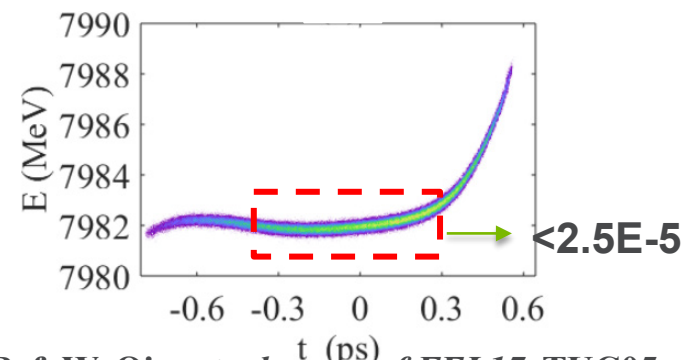
Argonne 
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EXTREMELY LOW ENERGY SPREAD FOR XFEL-OSCILLATOR



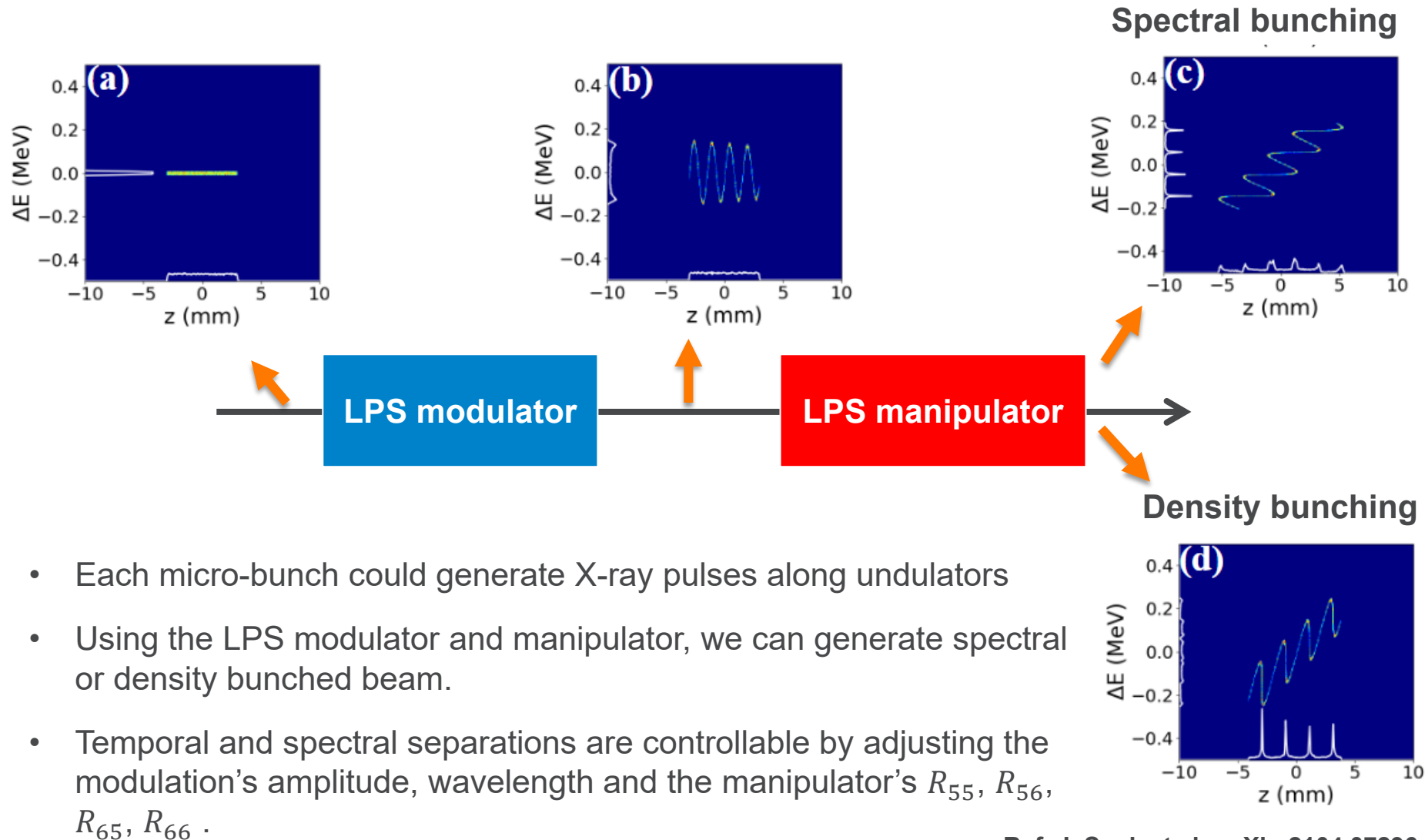
Ref. J. Seok et al., proc. of IPAC2019, WEPTS066

- On the LCLS-II HE lattice, bunch compressor 1 was replaced to a DEEX beamline, and bunch compressor 2 was removed.
- XFEL-Oscillator requires a bunch length of ~ 0.5 ps and an energy spread of $\sim 1E-5$
- DEEX beamline is feasible to lower the energy spread of entire beam by using additional higher order magnets.



Ref. W. Qin, et. al, proc. of FEL17, TUC05

MULTIENERGY BEAM FOR MULTICOLOR RADIATION



Ref. J. Seok et al., arXiv:2104.07296

DEMONSTRATION OF MULTIENERGY BEAM GENERATION VIA DOUBLE EMITTANCE-EXCHANGE

Laser pulse train

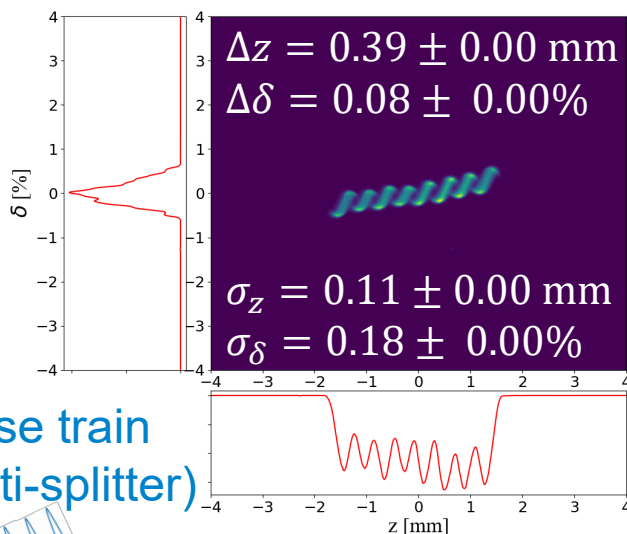


LPS modulator

DEEX beamline

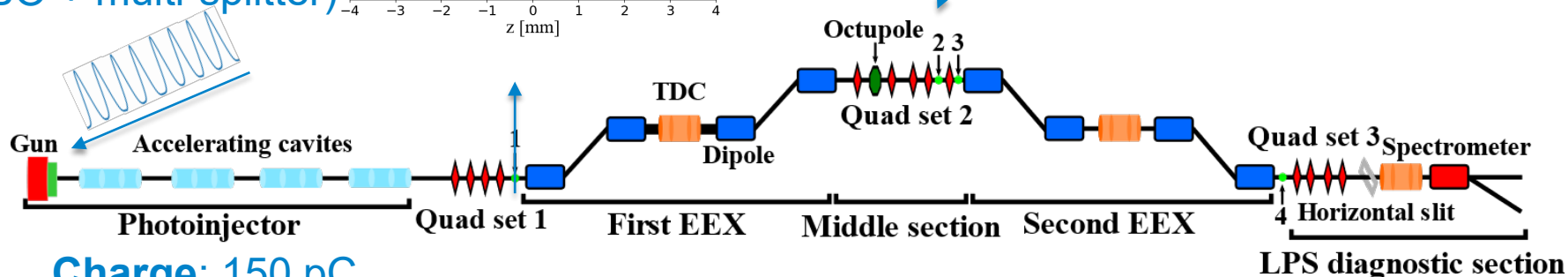


LPS manipulator



Laser pulse train
(BBO + multi-splitter)

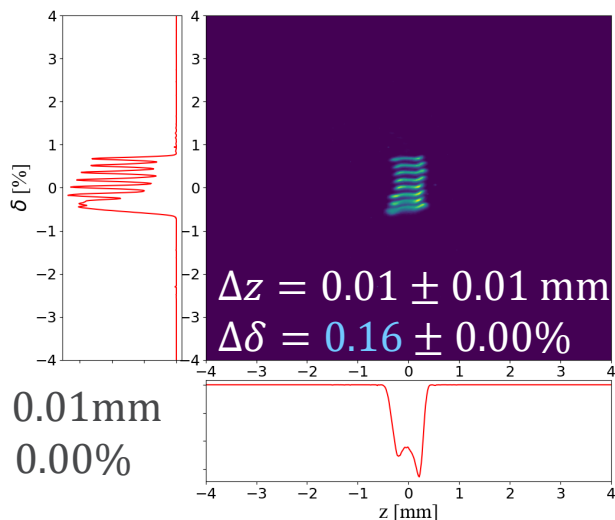
Transverse manipulation for bunching



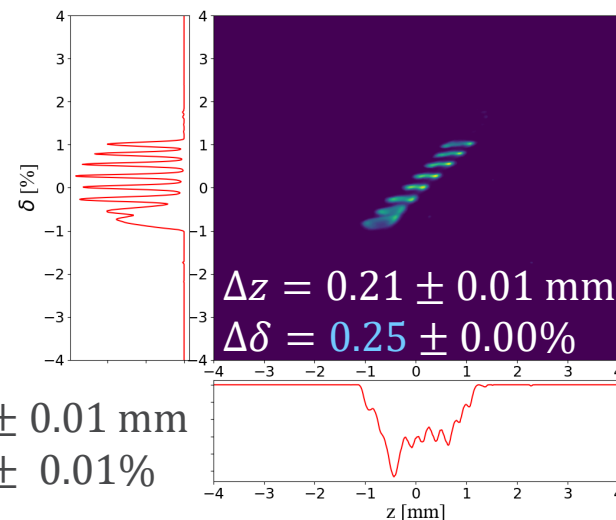
Charge: 150 pC

Energy: 44.5 MeV

SPECTRAL BUNCHING CASES

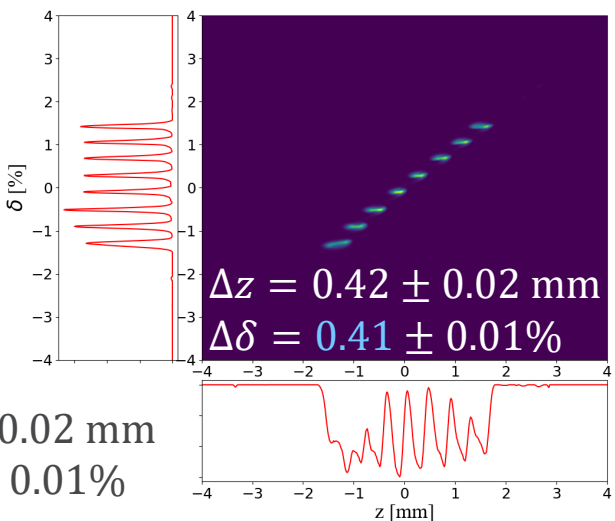


$\sigma_z = 0.29 \pm 0.01 \text{ mm}$
 $\sigma_\delta = 0.07 \pm 0.00\%$

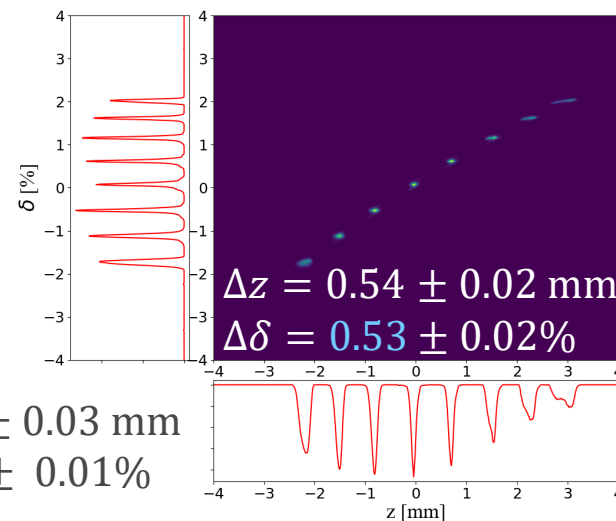


$\sigma_z = 0.20 \pm 0.01 \text{ mm}$
 $\sigma_\delta = 0.06 \pm 0.01\%$

Avg. of micro-bunches

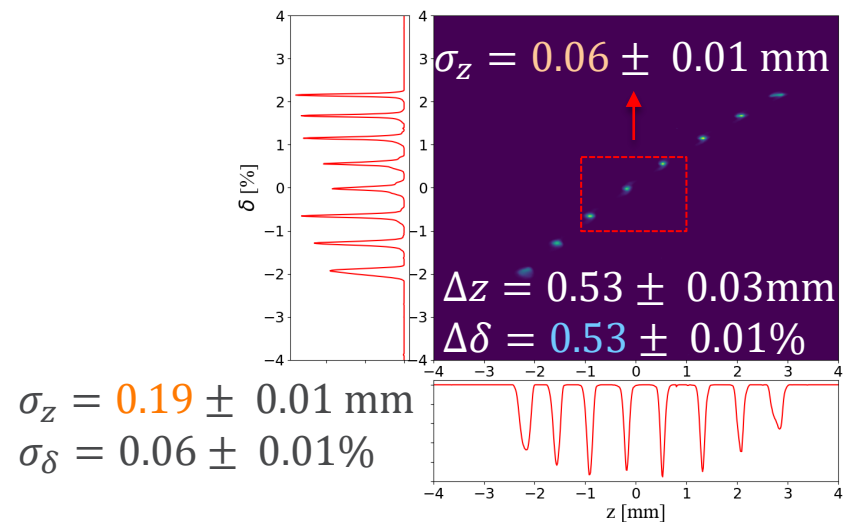
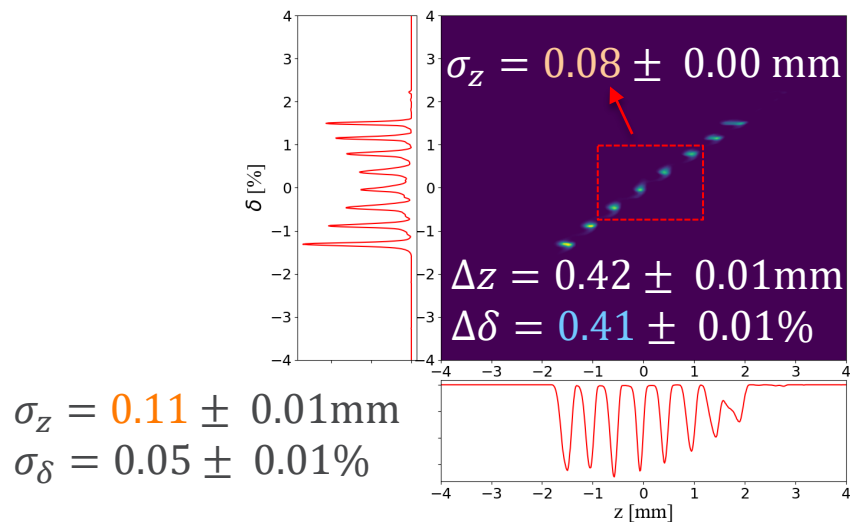
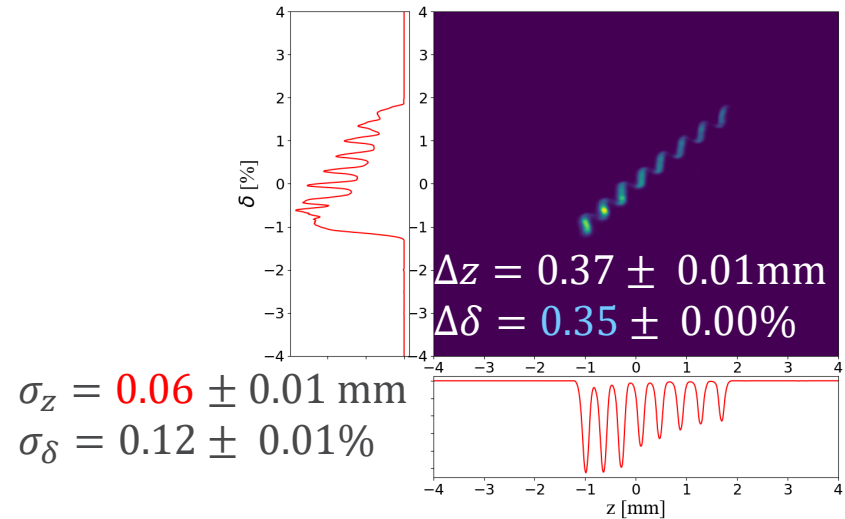
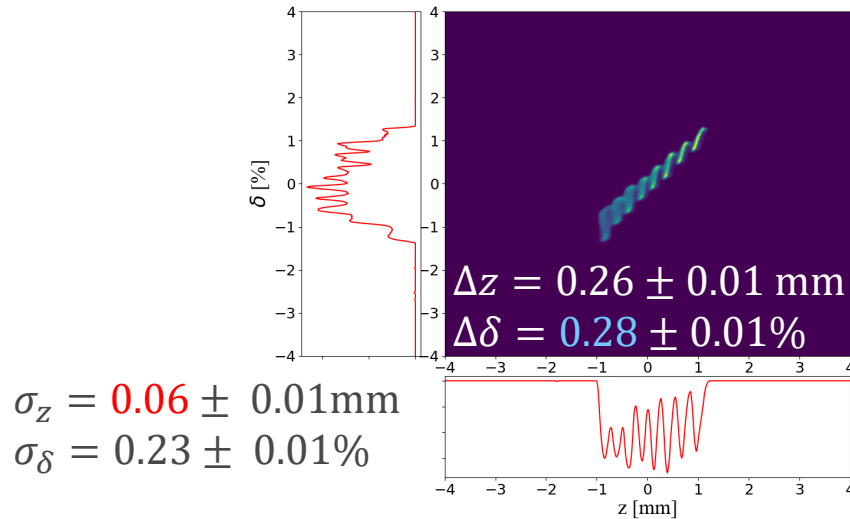


$\sigma_z = 0.17 \pm 0.02 \text{ mm}$
 $\sigma_\delta = 0.06 \pm 0.01\%$

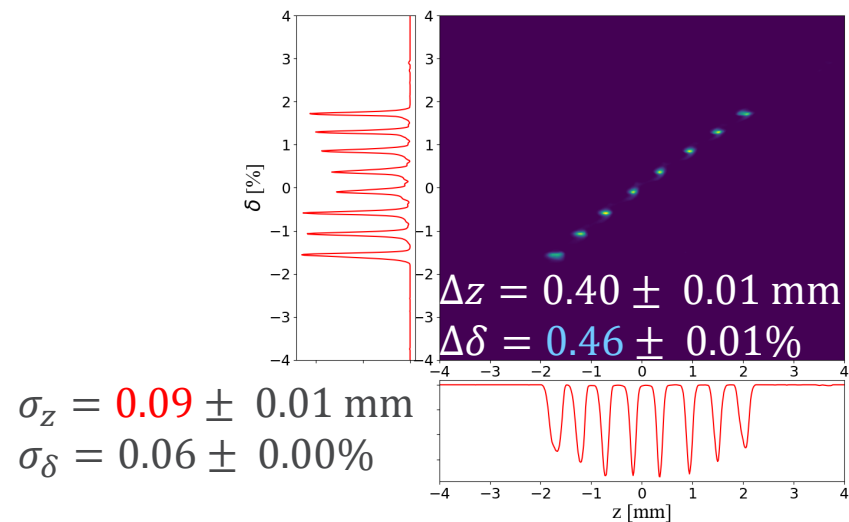
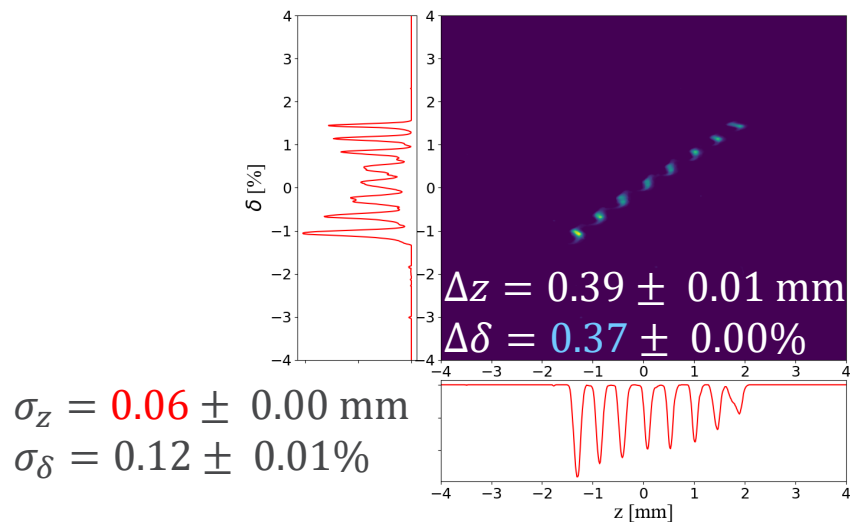
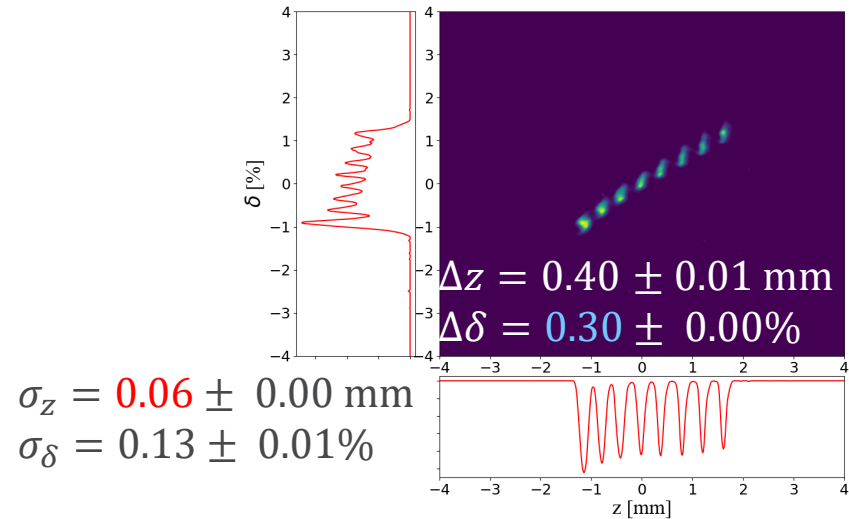
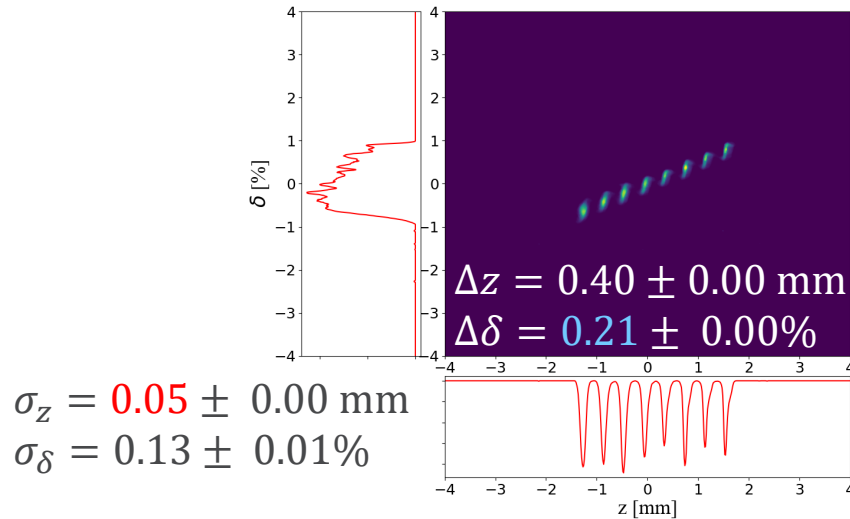


$\sigma_z = 0.14 \pm 0.03 \text{ mm}$
 $\sigma_\delta = 0.06 \pm 0.01\%$

DENSITY BUNCHING CASES



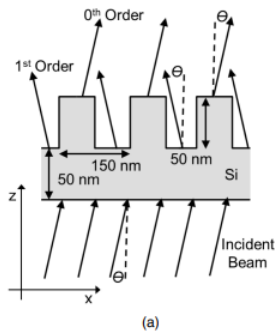
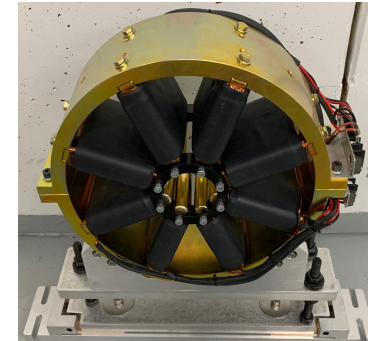
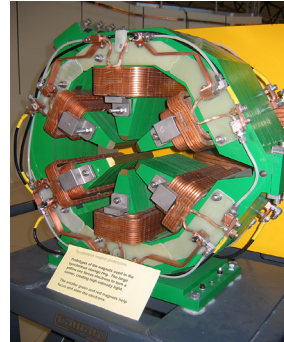
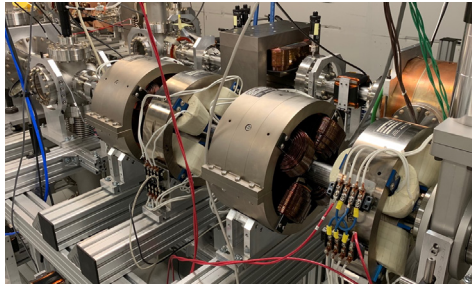
DENSITY BUNCHING WITH DIFFERENT ENERGY DEVIATION (FIXED SEPARATION)



SUMMARY

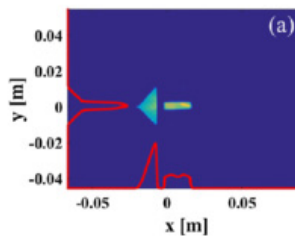
- Longitudinal manipulation is one of the modern accelerators' key techniques
- Double-EEX enables multiple longitudinal manipulation in advanced way
- We experimentally demonstrated i) tunable chirpless bunch compression, ii) tunable longitudinal chirp control, and iii) nonlinearity control
- Double-EEX may be interesting new options for XFEL-O and multi-color radiation sources

DEEX BEAMLINE AS MULTIFUNCTIONAL LPS MANIPULATION PLATFORM



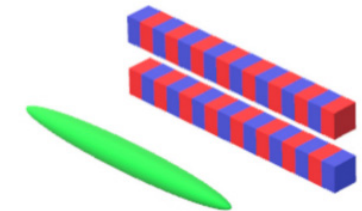
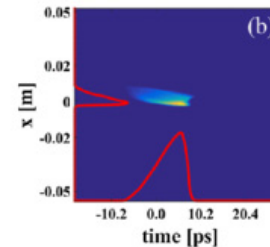
Crystal Si grating

Ref. E. A. Nanni *et al.*, PRAB 21, 014401 (2018)



Mask

Ref. Q. Gao *et al.*, PRL 120, 114801 (2018)



Transverse wiggler

Ref. G. Ha *et al.*, proc of IPAC2019, TUPGW089, 2019

THANK YOU FOR YOUR ATTENTION



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