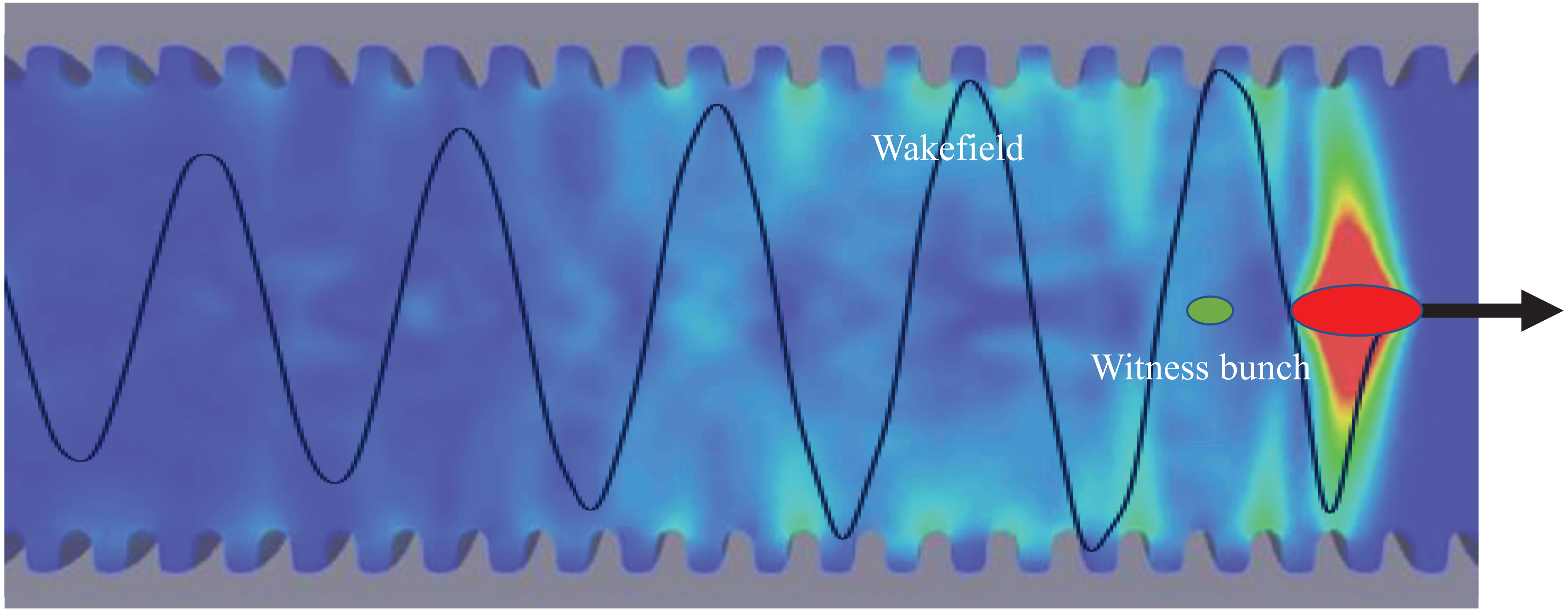
Longitudinal-Phase-Space Manipulation for Efficient Beam-Driven Structure Wakefield Acceleration

Wei Hou, TAN
Northern Illinois University
Philippe, PIOT
Northern Illinois University and Fermilab
Alexander, ZHOLENTS
Argonne National Laboratory

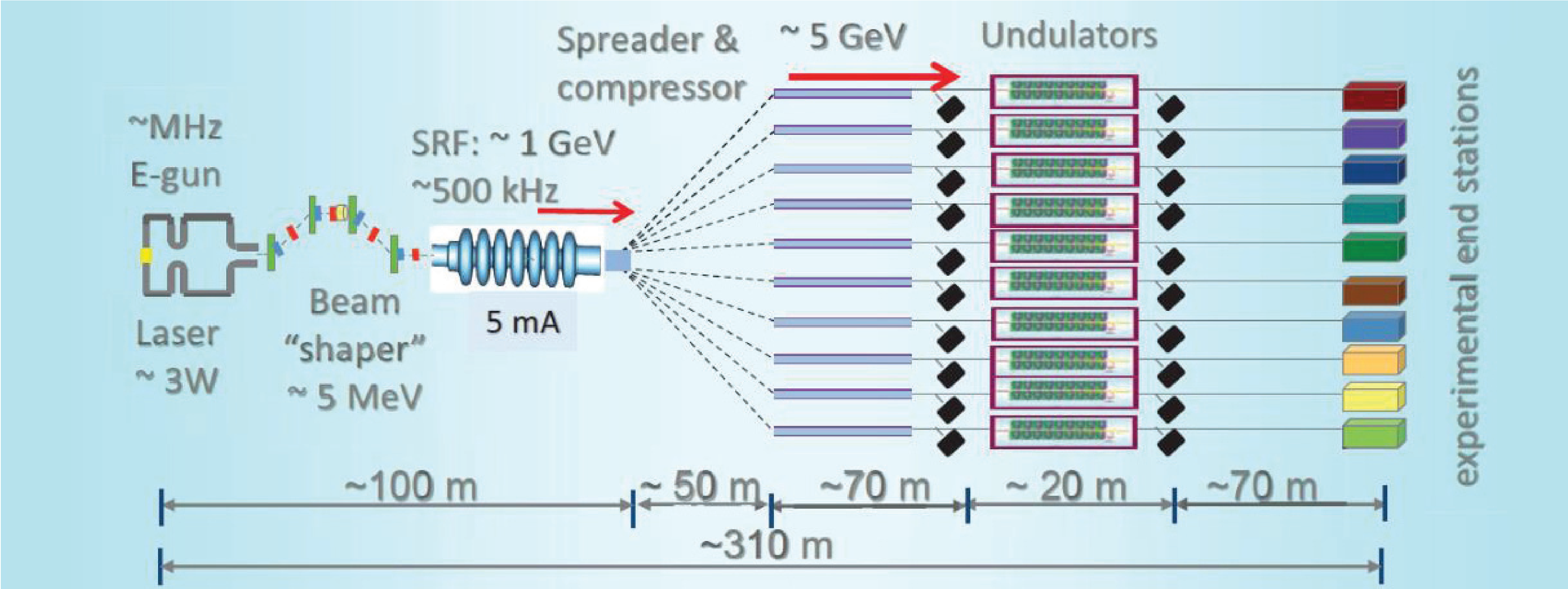
Beam-driven Structure WakeField Acceleration (SWFA)



Simulation was done using ACE3P[1], visualization was done using Paraview[2].

1. C. Ng et al, Massively parallel electromagnetic ACE3P Simulation Suite. SLAC National Accelerator Laboratory.
2. J. Ahrens, B. Geveci, and C. Law, ParaView: An End-User Tool for Large Data Visualization, vol. 717. Elsevier, 2005

X-ray FEL user facility using beam-driven SWFA[1,2]

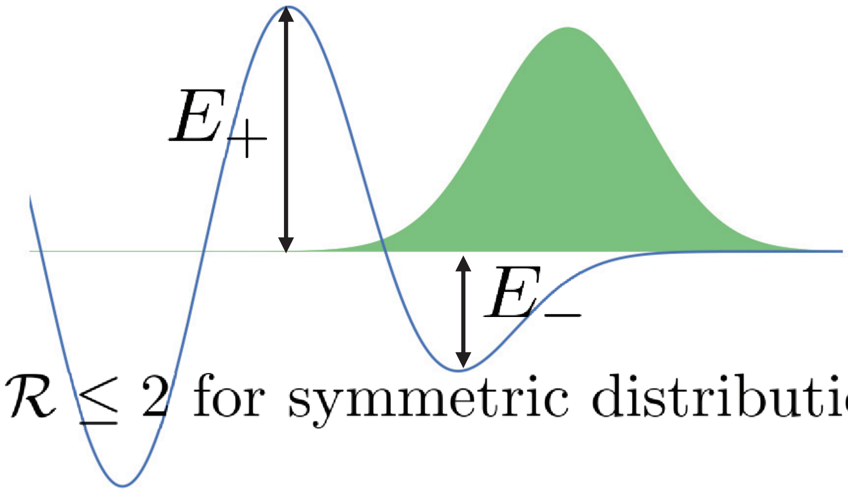


- Compact
- Multi user facility
- High field gradient, ~100 MV/m
- High repetition rate (Using SRF linac to supply drive and witness bunches)

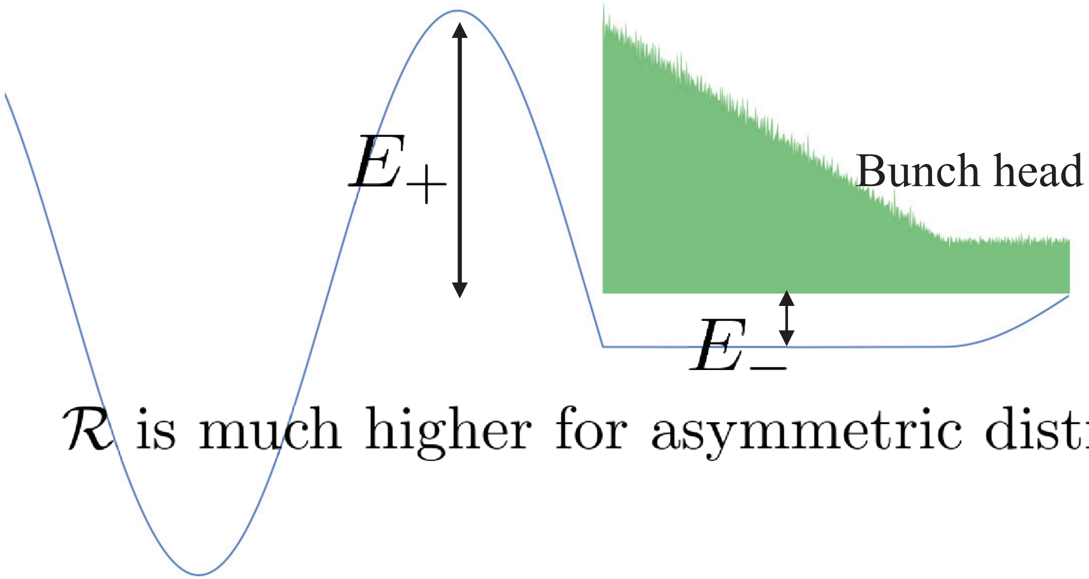
1. J. G. Power, "A Conceptual Design of a Compact Wakefield Accelerator for a High Repetition Rate Multi User X-ray Free-Electron Laser Facility," Geneva, Switzerland, Jun-2018.
2. A. Zholents, et al., Nucl. Instrum. Meth. A 829 (2016)190-193

Wakefield and transformer ratio[1]

$$\mathcal{R} = \left| \frac{E_+}{E_-} \right|$$



$\mathcal{R} \leq 2$ for symmetric distribution.



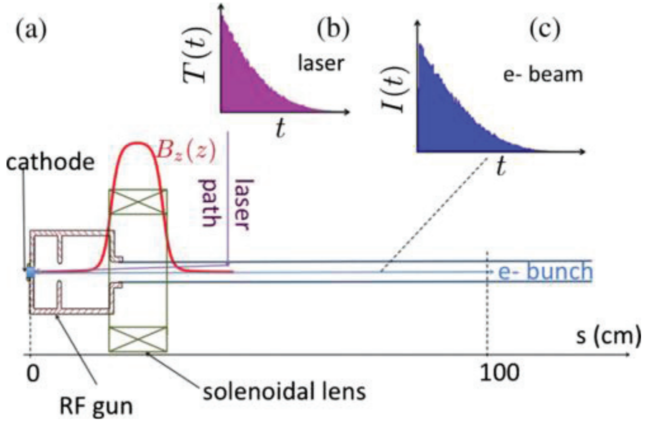
$\mathcal{R}$ is much higher for asymmetric distribution.

1. K. L. Bane et. al. *IEEE Trans. Nucl. Sci.*, vol. 32, pp. 3524–3526, 1985.

Various techniques of beam shaping

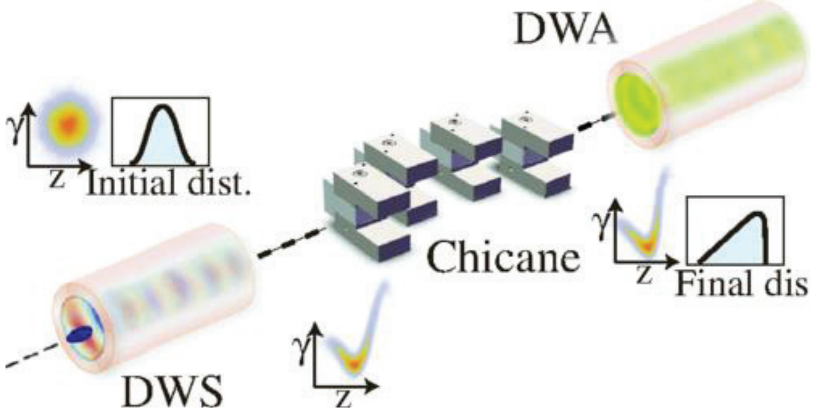
Laser Shaping at photocathode

[F. Lemery and P. Piot, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 18, no. 8, p. 081301, Aug. 2015]



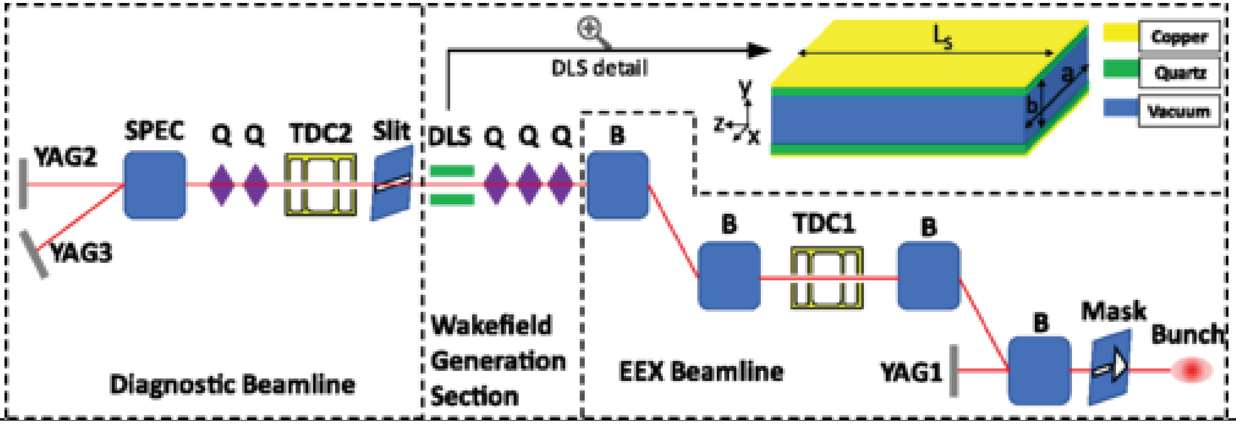
Self wakefields

[G. Andonian *et al.*, *Phys. Rev. Lett.*, vol. 118, no. 5, p. 054802, Feb. 2017.]



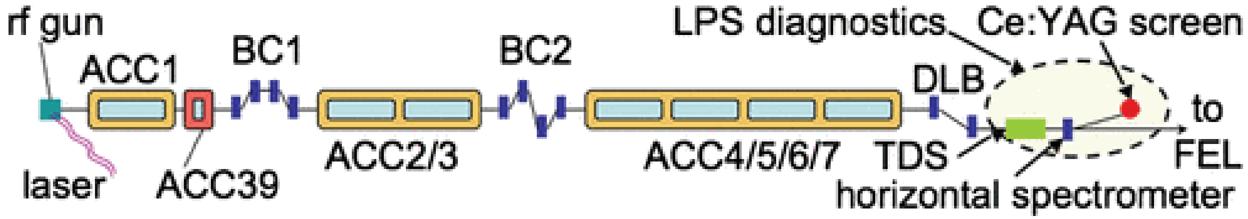
Emittance exchange

[Q. Gao *et al.*, *Phys. Rev. Lett.*, vol. 120, no. 11, p. 114801, Mar. 2018.]



Using SRF linac

[P. Piot *et al.*, *Phys. Rev. Lett.*, vol. 108, no. 3, p. 034801, Jan. 2012.]

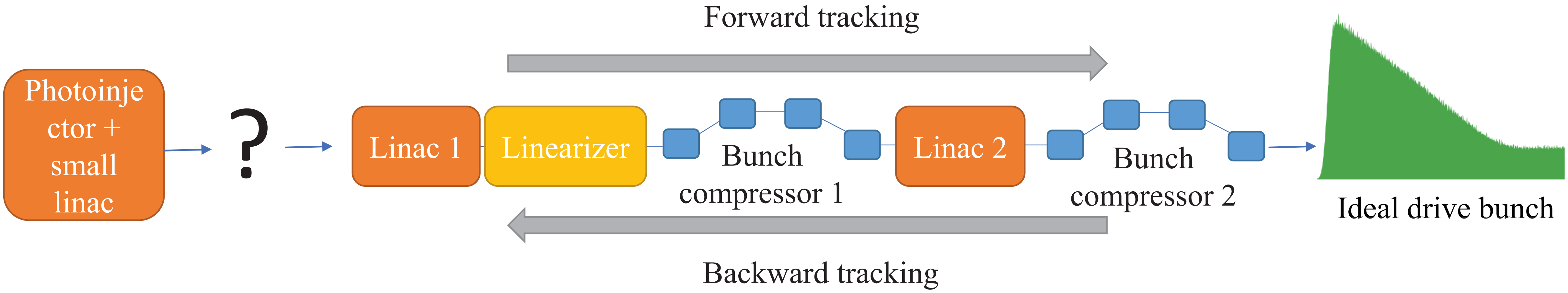


Northern Illinois University

Argonne NATIONAL LABORATORY

Longitudinal phase space manipulation for beam-driven SWFA

- Studied the longitudinal beam dynamics to produce ideal drive bunch using SRF linac
- Employed self-written longitudinal tracking code[1] for our studies
- Used forward and backward tracking[2] simulation to guide us



1. W. Tan et al, *2018 IEEE Advanced Accelerator Concepts Workshop (AAC)*, 2018, pp. 1–5.
2. M. Cornacchia et al, *Phys. Rev. ST Accel. Beams*, vol. 9, no. 12, p. 120701, Dec. 2006.

Longitudinal dynamics

$$(\zeta_i, E_i) \xrightarrow{\text{LPS transformation}} (\zeta_f, E_f)$$

RF acceleration	Collective effects
$\zeta_f = \zeta_i$ $E_f = E_i \pm eV_{\mathrm{RF}} \cos\left(\phi - \frac{2\pi f}{c}\zeta_i\right)$ bunch compression $\zeta_f = \zeta_i \pm \left(R_{56}\delta_i + T_{566}\delta_i^2\right)$, $E_f = E_i$ $\delta_i \equiv \frac{E_i - E_{\mathrm{ref}}}{E_{\mathrm{ref}}}$ $E_{\mathrm{ref}} = E(\zeta = 0)$ bunch head at $\zeta > 0$	$\zeta_f = \zeta_i$ $E_f(\zeta_i) = E_i(\zeta_i) \pm \Delta E(\zeta_i)$ • Structure wakefield : user-defined Green's function • Longitudinal space charge (LSC) : impedance model[1] • Coherent synchrotron radiation : 1D steady-state model is implemented[2]

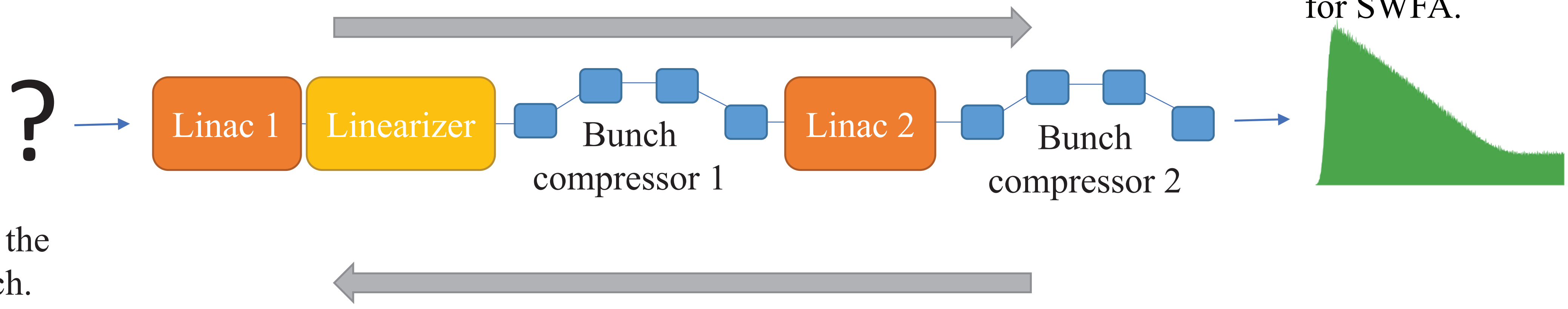
"+" denotes forward tracking, "-" denotes backward tracking

1. J. Qiang et al, *Phys. Rev. ST Accel. Beams*, vol. 12, no. 10, p. 100702, Oct. 2009.
2. E. L. Saldin et al, *Nucl. Instrum. Meth. A*, vol. 398, no. 2, pp. 373–394, 1997.

Simulation studies

5. Forward tracking.

1. Generate an ideal drive bunch for SWFA.

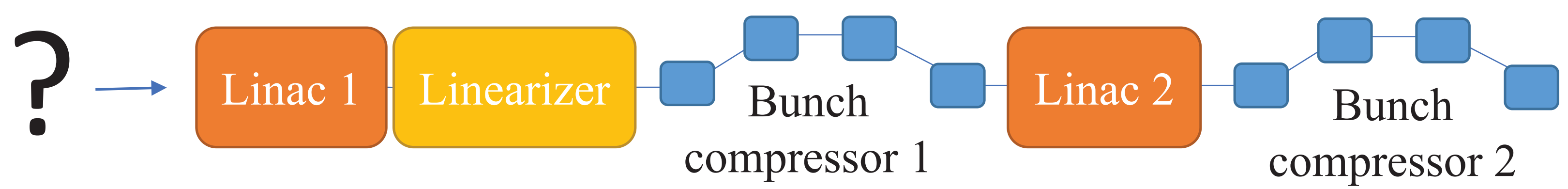


3. Analyze the initial bunch.

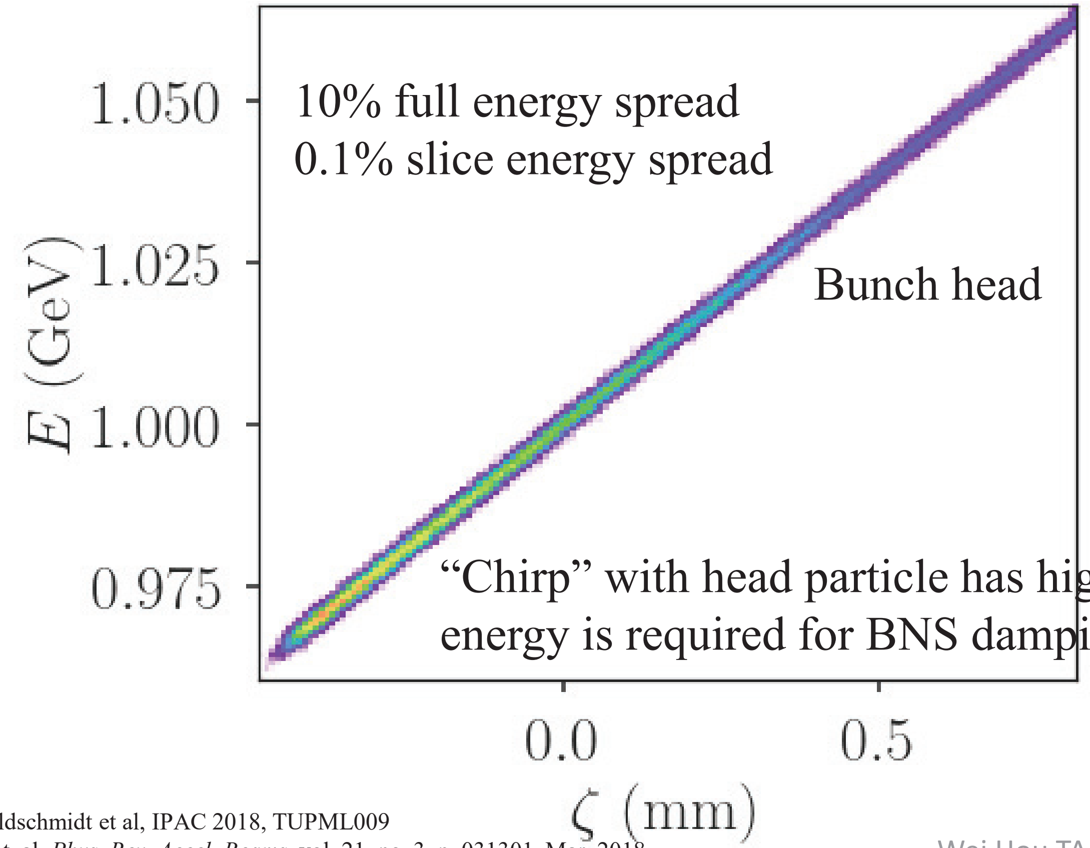
2. Backward tracking and optimize accelerator parameters.

4. Repeat.

Simulation studies – drive bunch

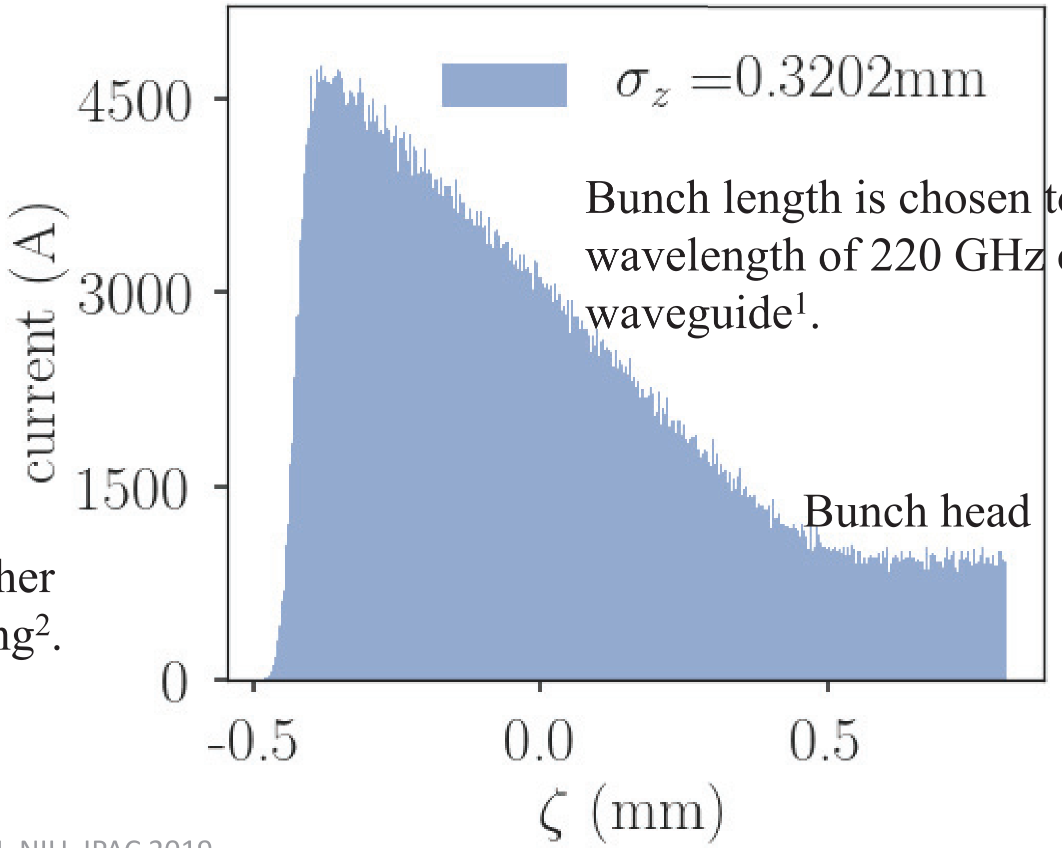


1 GeV, 10 nC
~100k macroparticles



10% full energy spread
0.1% slice energy spread

"Chirp" with head particle has higher energy is required for BNS damping[2].



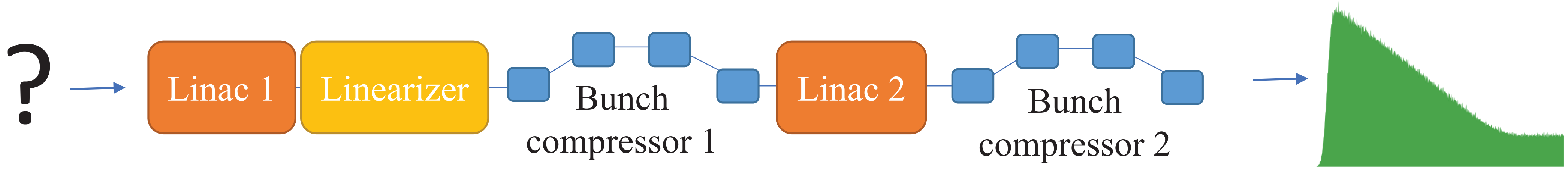
Bunch length is chosen to match the wavelength of 220 GHz corrugated waveguide[1].

1. G. J. Waldschmidt et al, IPAC 2018, TUPML009
2. Baturin et. al. *Phys. Rev. Accel. Beams*, vol. 21, no. 3, p. 031301, Mar. 2018.

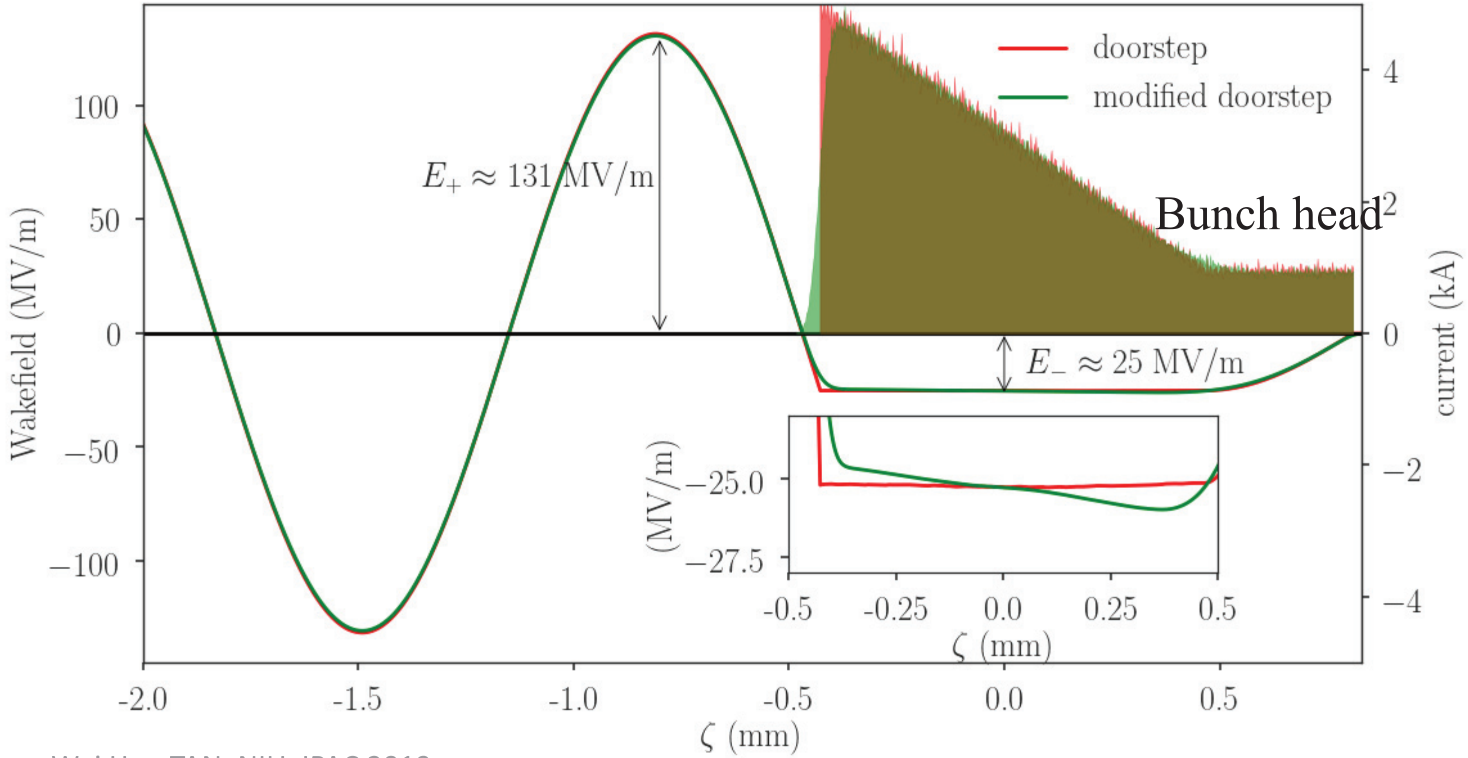
Northern Illinois University

Argonne NATIONAL LABORATORY

Simulation studies – drive bunch

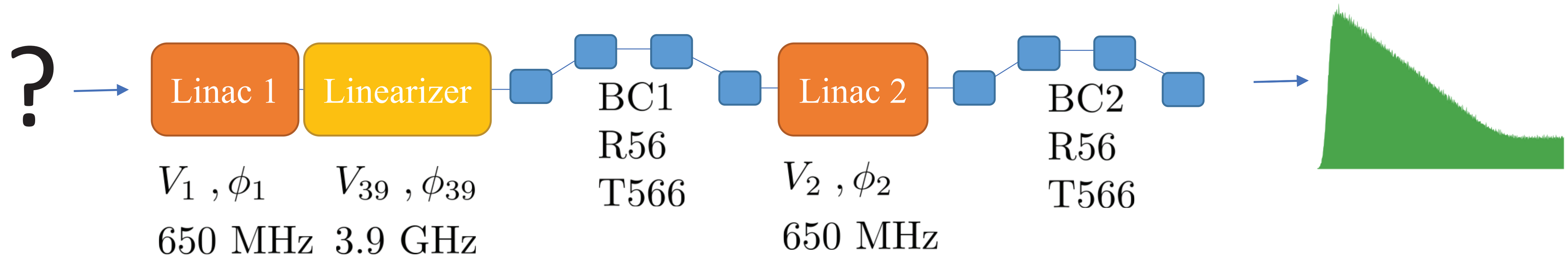


- Wakefield within doorstep is uniform
- Wakefield within modified doorstep is not uniform
- It is required for maintain linear chirp as the bunch passing through a corrugate waveguide to maintain its stability[1]



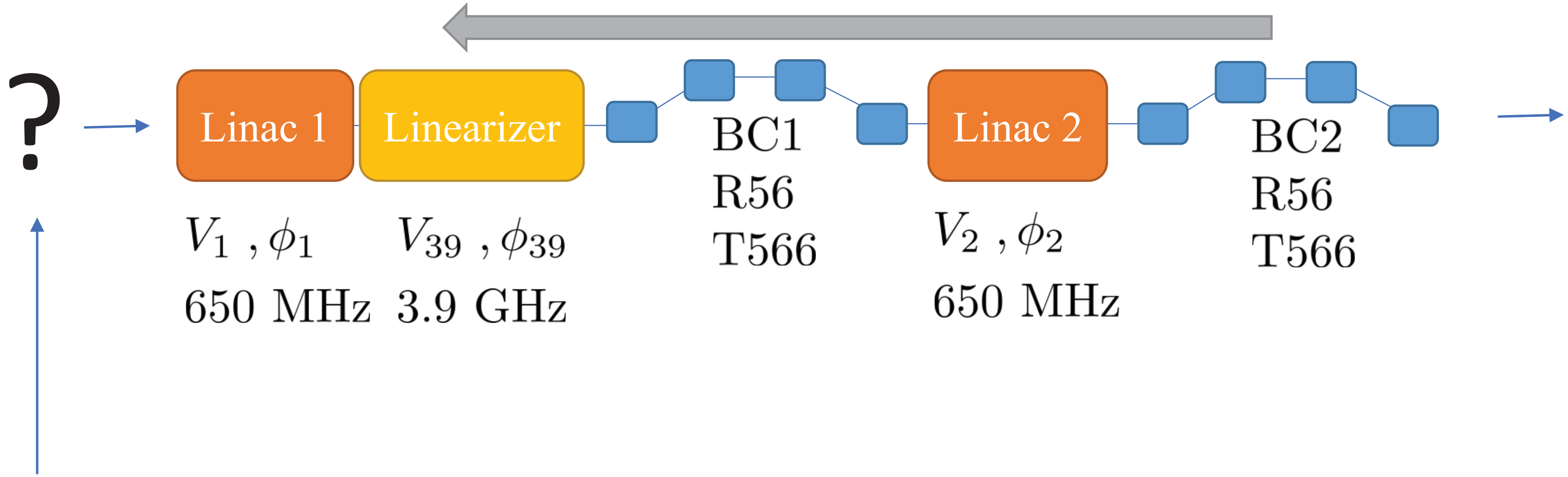
1. Baturin et. al. *Phys. Rev. Accel. Beams*, vol. 21, no. 3, p. 031301, Mar. 2018.

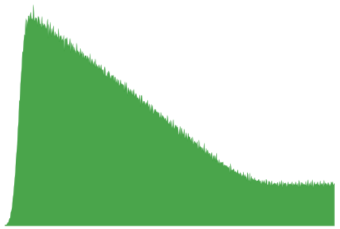
Simulation studies – backward tracking



- Structure wakefields generated within linacs and linearizer are calculated using Green's function of respective cavity
- Longitudinal space charge (LSC) are calculated within linacs and linearizer
- Bunch compressors (BCs) are represented by R56, T566
- R56 < 0 (we need a positive chirp for BNS damping, which is different from the standard C-shaped chicane)
- CSR is treated as four energy kicks within BCs, for simplicity, each energy kick is treated as if the bunch passing through a 40 cm dipole magnet with 8 degree bending angle

Simulation studies – backward tracking

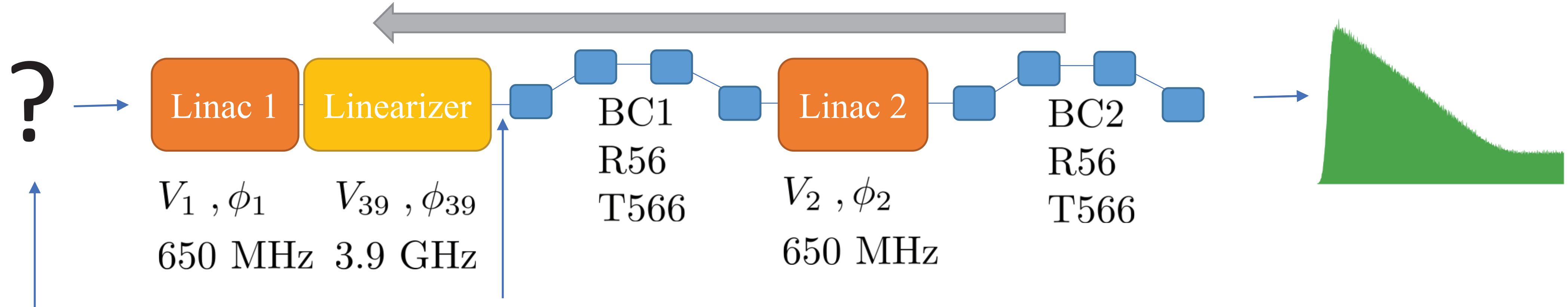




Criteria for initial bunch

- Peak current lower than 300 A
- Mean energy lower than 70 MeV
- Full energy spread lower than 10% of mean energy
- A distribution that can be produced from a photoinjector

Simulation studies – Optimization



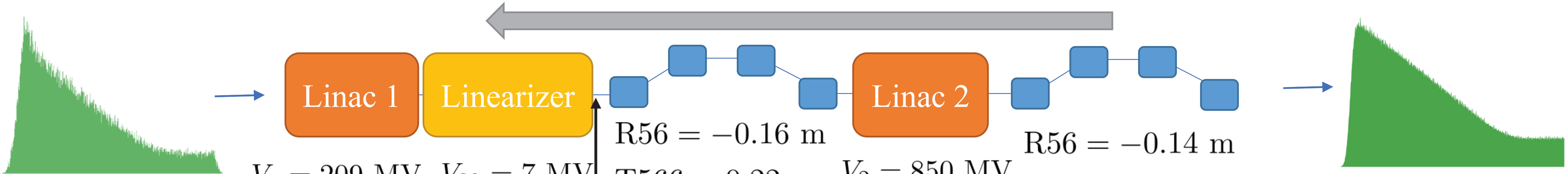
$$\delta = c_0 + c_1\zeta + c_2\zeta^2 + c_3\zeta^3$$

minimize $\frac{c_2}{c_1}$, before bunch compressor 1 and before linac 1

- We impose a condition that the chirp of drive beam must be same sign for the whole bunch, before BC1 and before linac 1
- Python package, DEAP[1] is used for multi-objective optimization

1. Félix-Antoine Fortin et al, *J. Mach. Learn. Res.* 13, 1 (July 2012), 2171-2175.

Simulation studies – Optimization result



Initial bunch

$V_1 = 209$ MV
$\phi_1 = 18°$
650 MHz

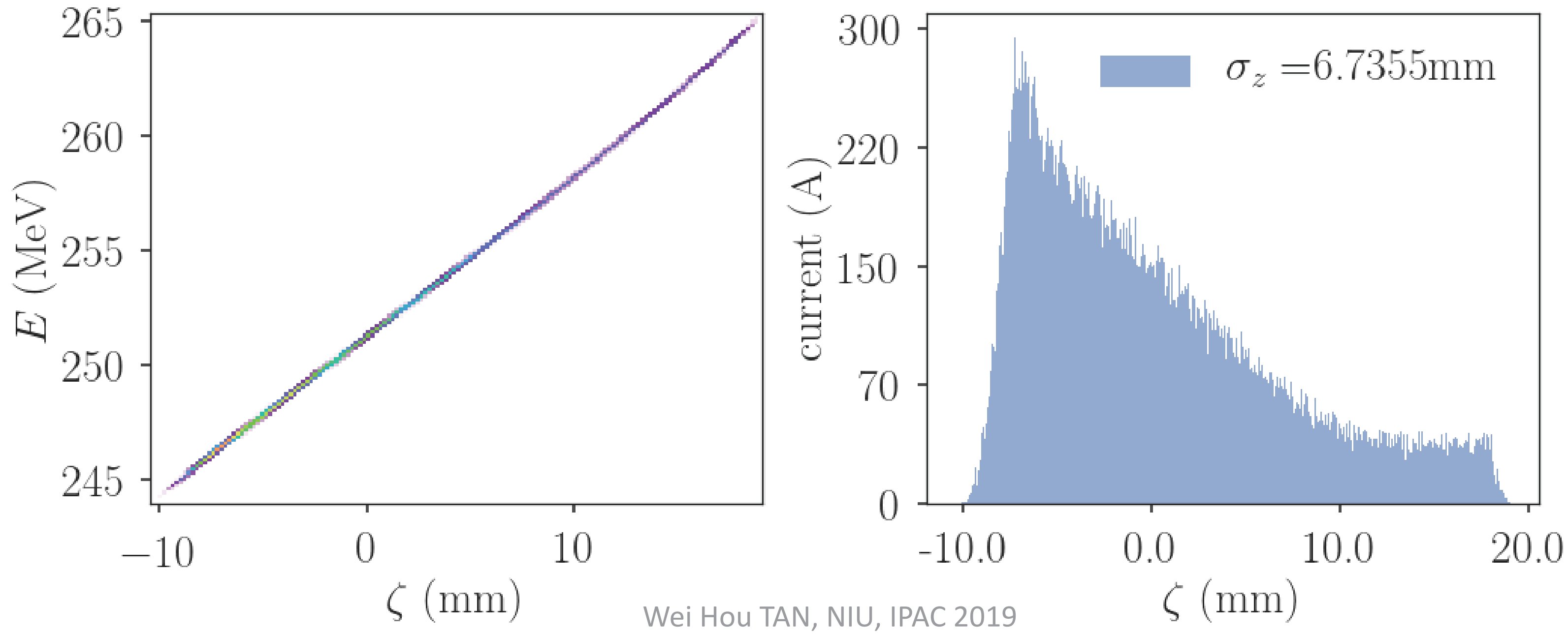
$V_{39} = 7$ MV
$\phi_{39} = 219°$
3.9 GHz

R56 $= -0.16$ m
T566 $= 0.22$ m

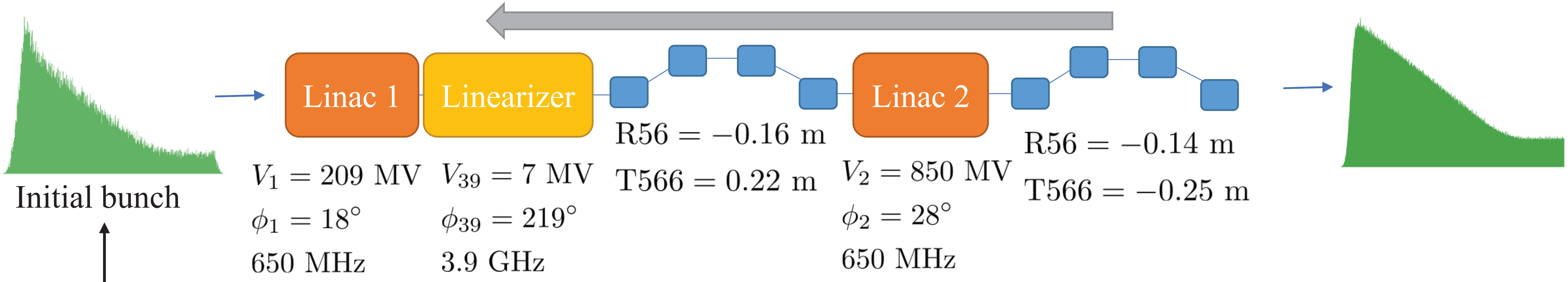
$V_2 = 850$ MV
$\phi_2 = 28°$
650 MHz

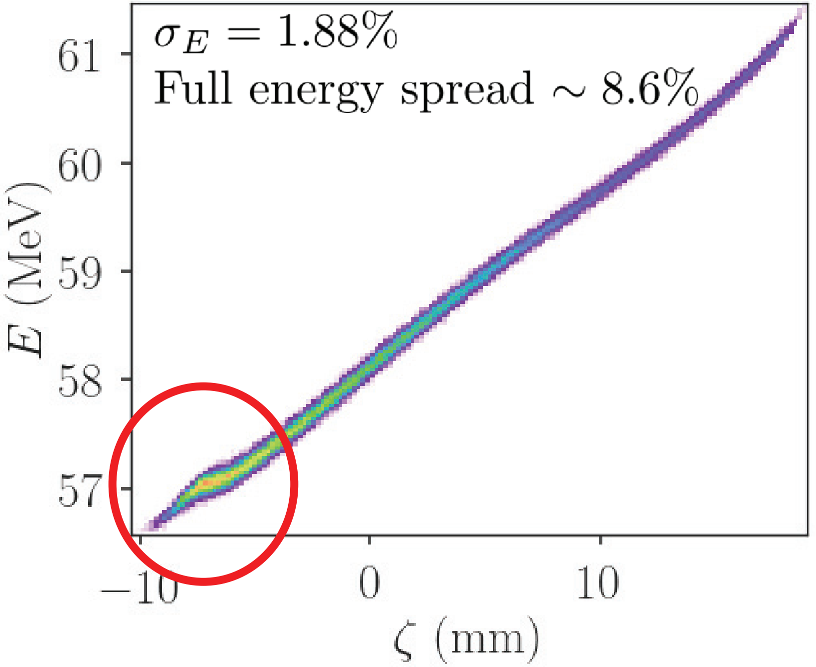
R56 $= -0.14$ m
T566 $= -0.25$ m

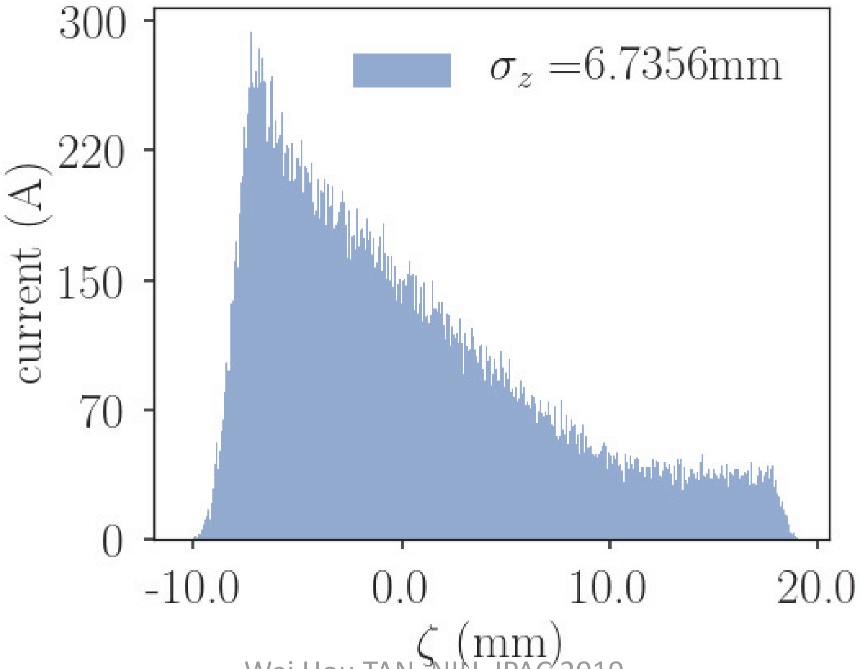
Bunch before BC1 and after Linearizer



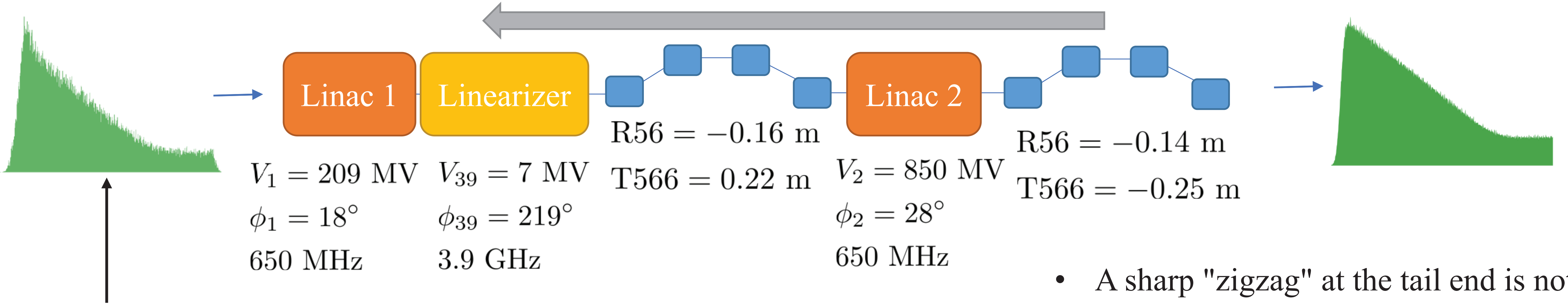
Simulation studies – Initial bunch



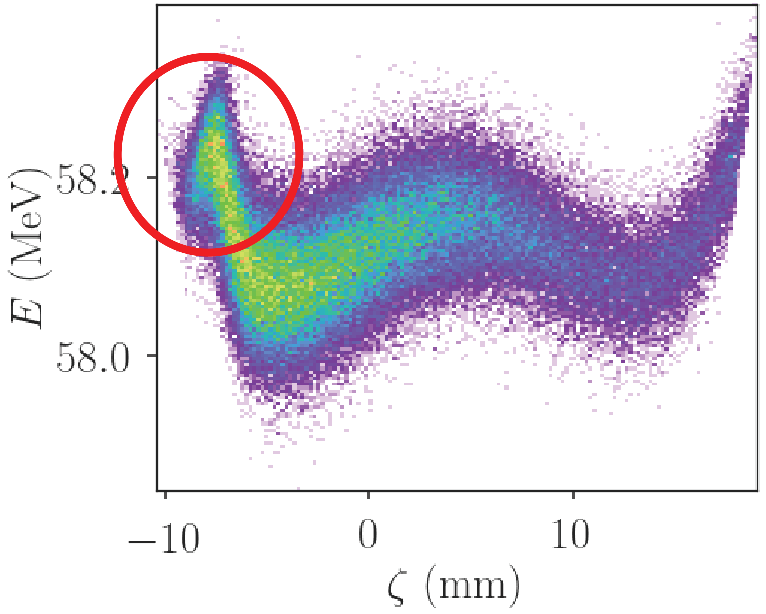


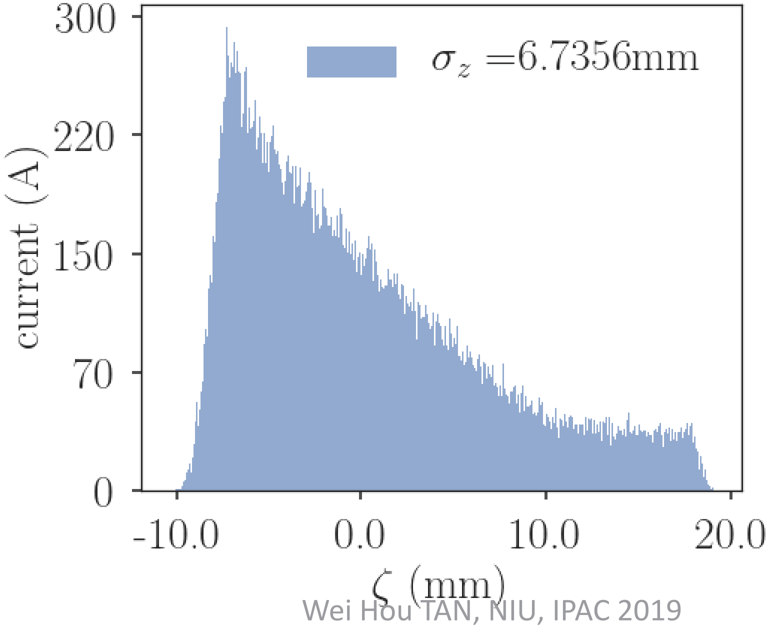


Simulation studies – Initial bunch



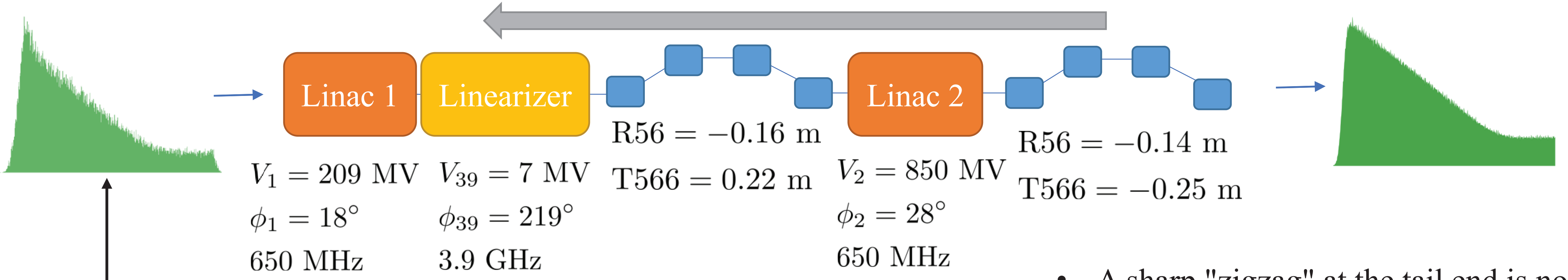
After removing the linear chirp



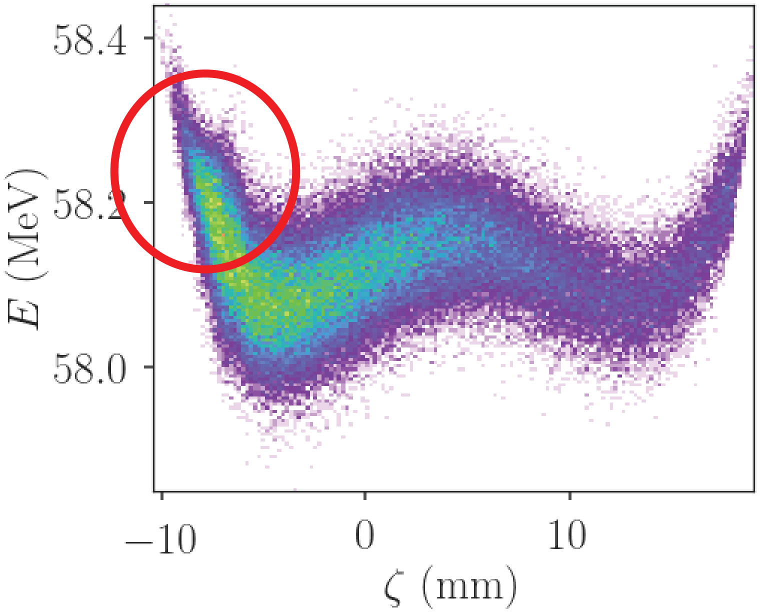


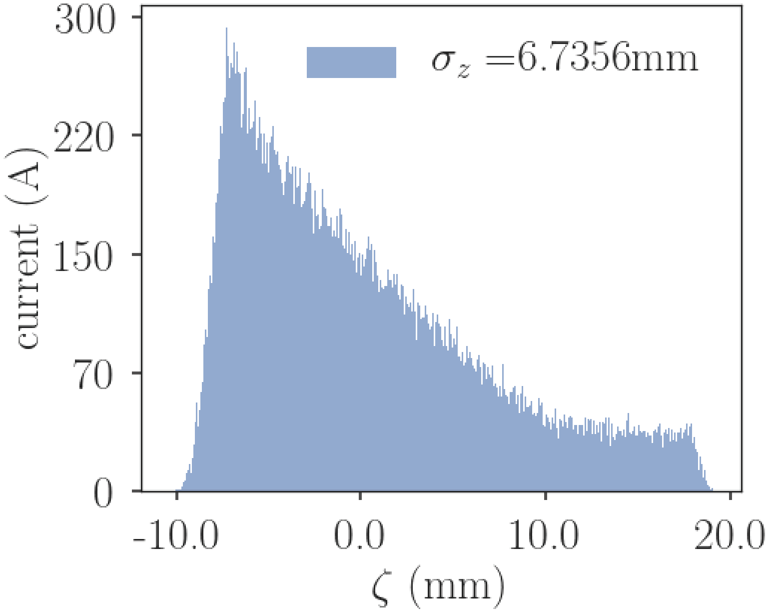
- A sharp "zigzag" at the tail end is not easy to make
- Thus in forward tracking we use smoother distribution assuming that it can be produced from a photoinjector

Simulation studies – Initial bunch



After removing the linear chirp

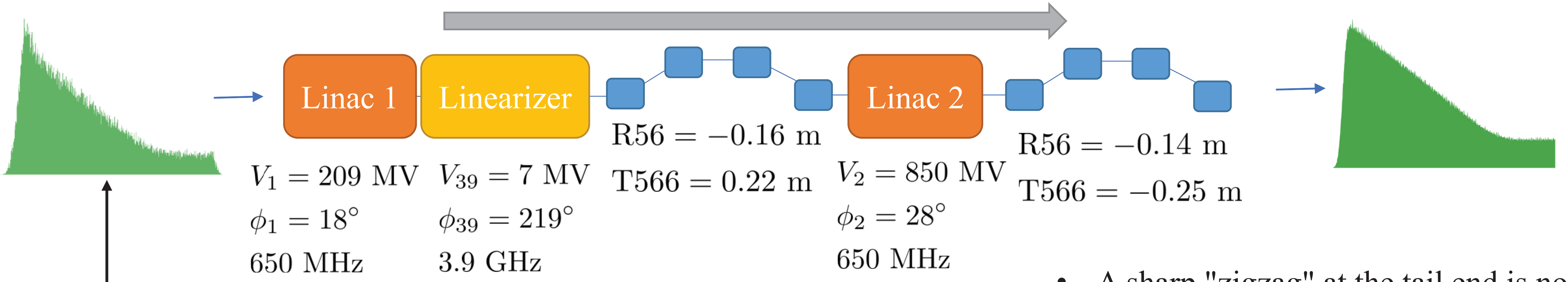


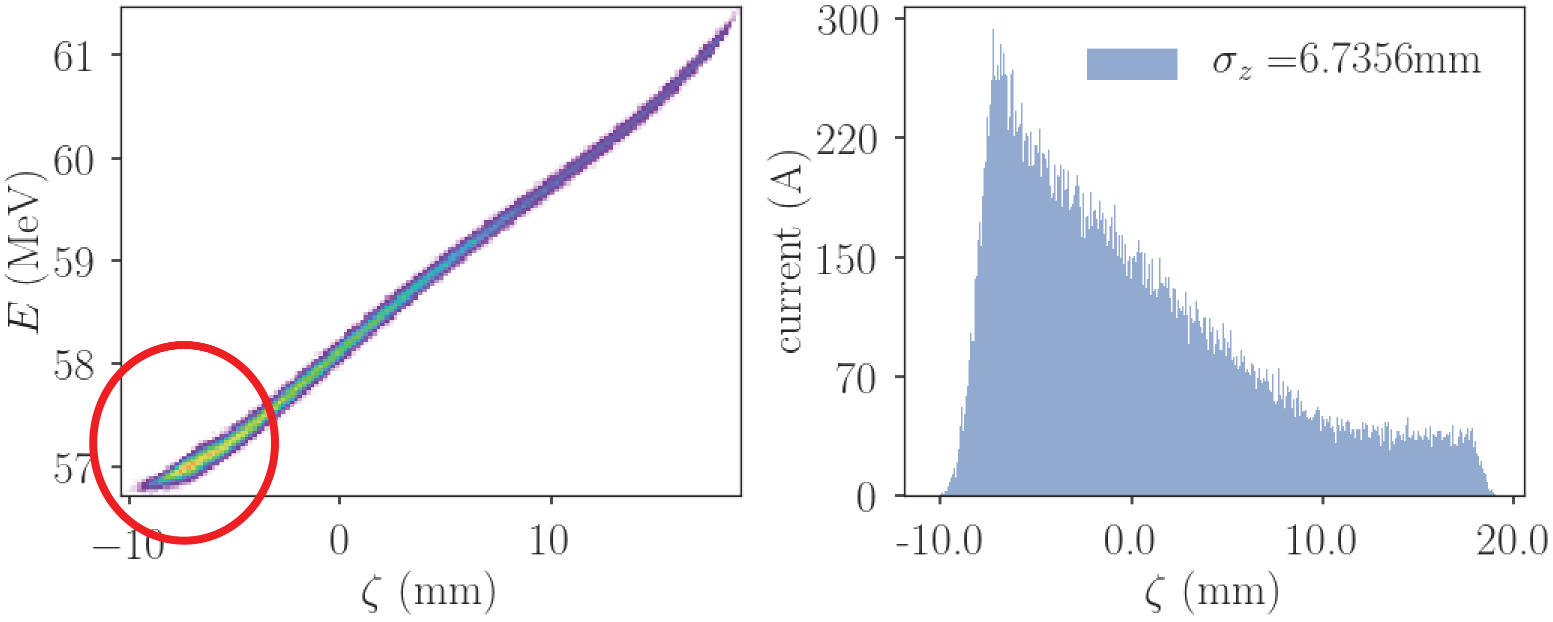


- A sharp "zigzag" at the tail end is not easy to make
- Thus in forward tracking we use smoother distribution assuming that it can be produced from an electron gun
- The sinusoidal-like oscillation can be achieved through a waveguide dechirper[1]

1. Z. Zhang *et al.*, *Phys. Rev. ST Accel. Beams*, vol. 18, no. 1, p. 010702, Jan. 2015.

Simulation studies – Forward tracking

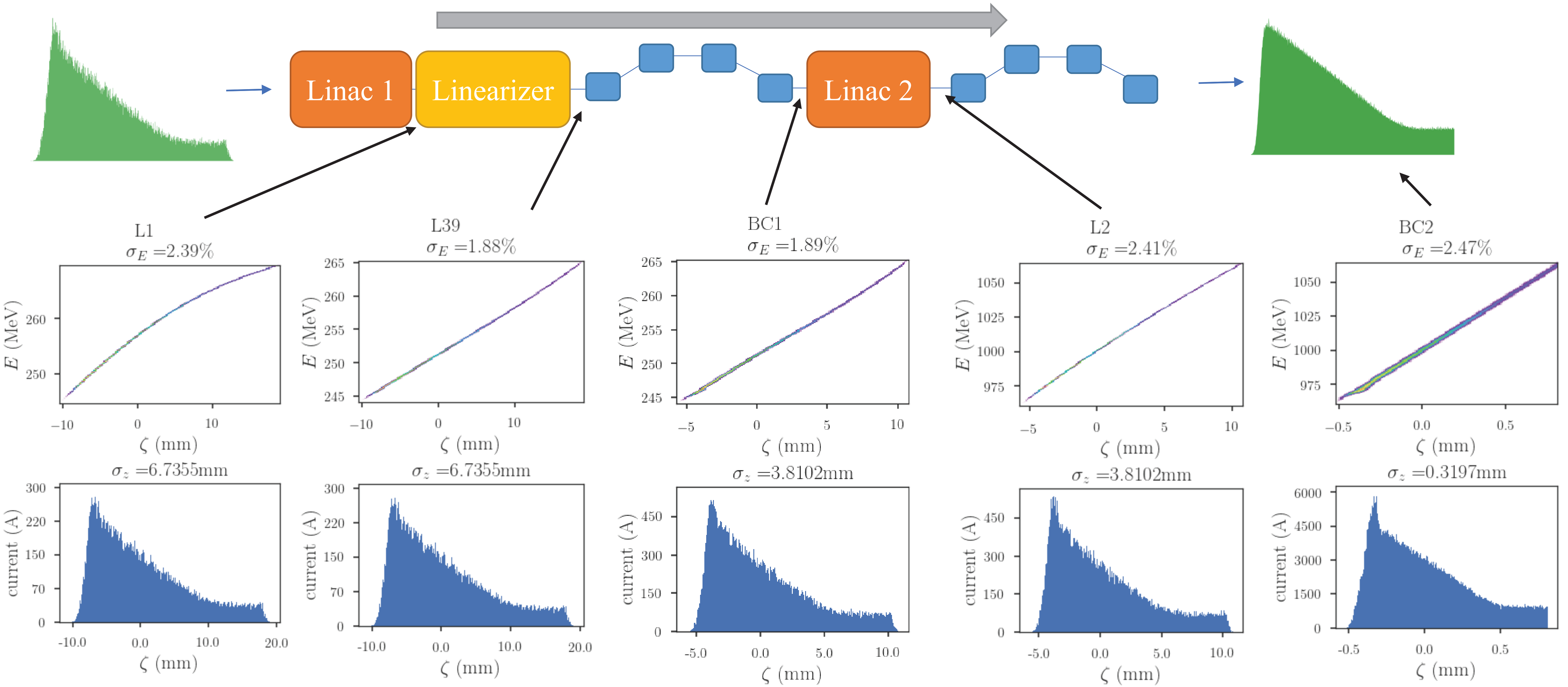




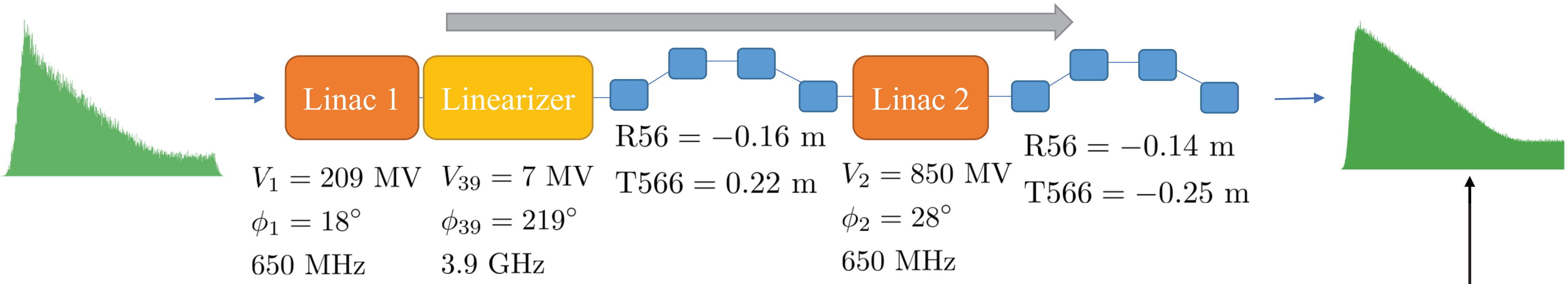
- A sharp "zigzag" at the tail end is not easy to make
- Thus in forward tracking we use smoother distribution assuming that it can be produced from an electron gun
- The sinusoidal-like oscillation can be achieved through a waveguide dechirper[1]

1. Z. Zhang *et al.*, *Phys. Rev. ST Accel. Beams*, vol. 18, no. 1, p. 010702, Jan. 2015.

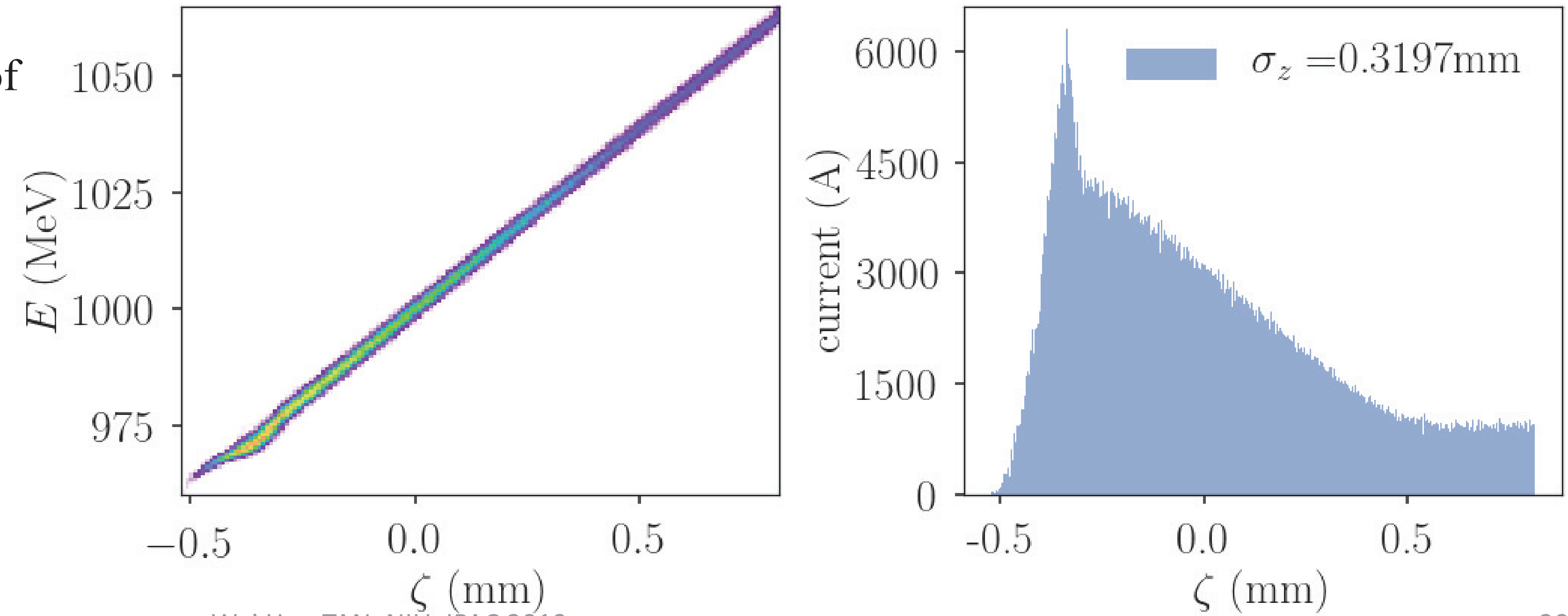
Simulation studies – Forward tracking



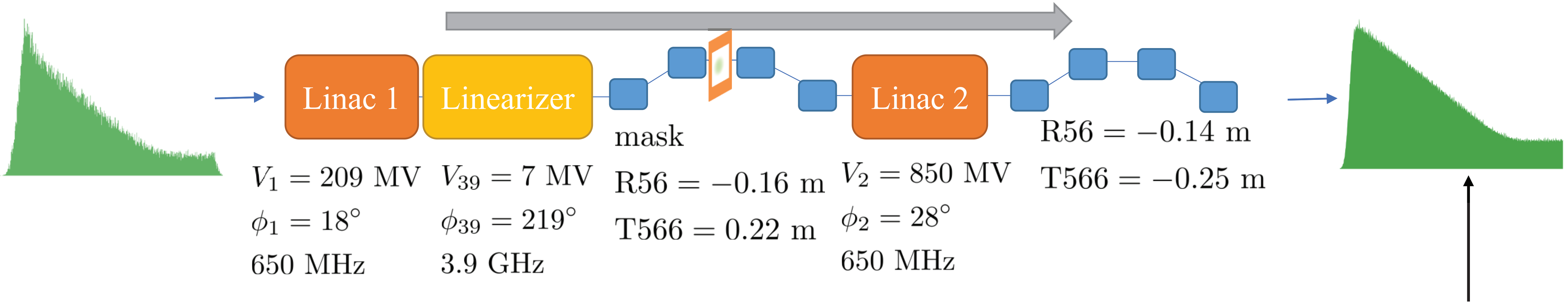
Simulation studies – Forward tracking



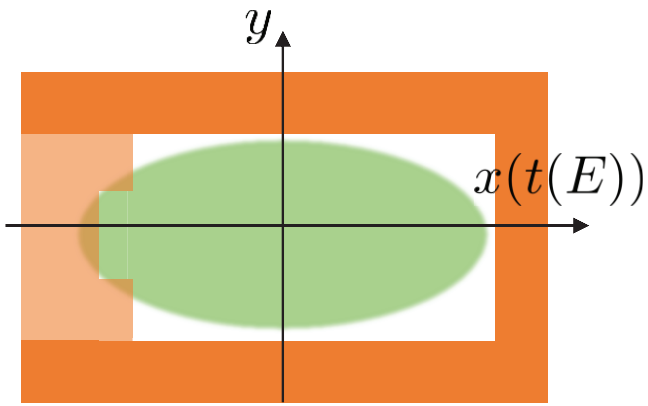
- The final bunch has the unwanted spike
- We remove it using mask in the middle of BC1.



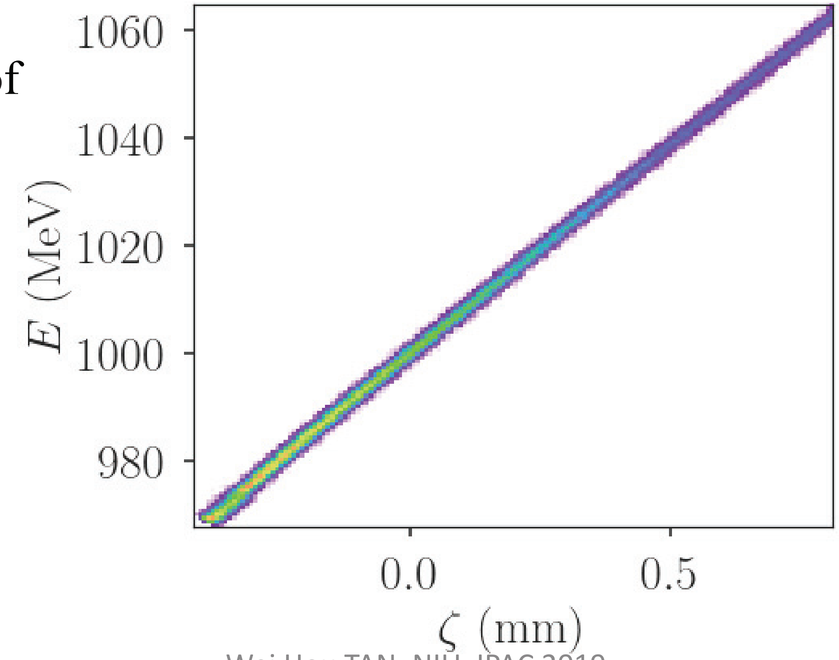
Simulation studies – Forward tracking + mask

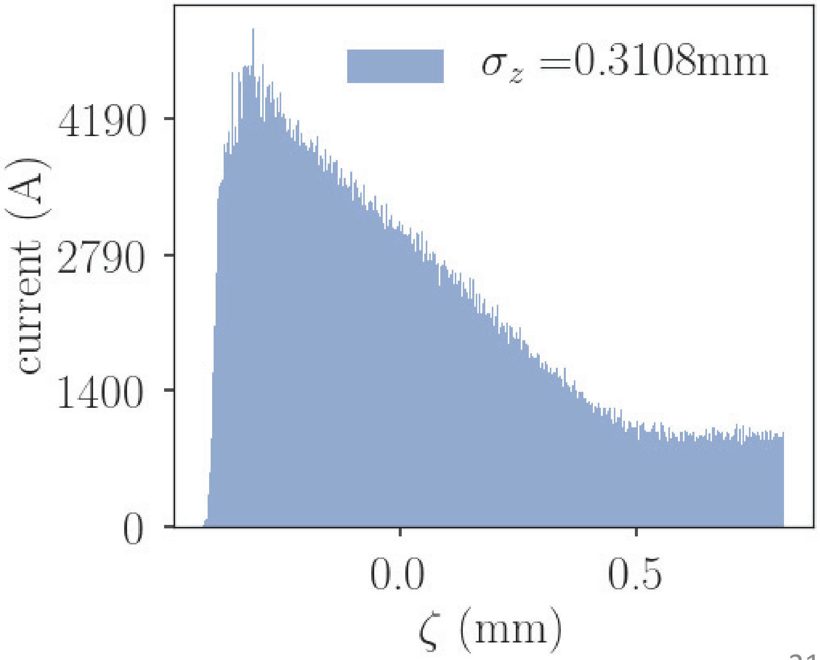


- The final bunch has the unwanted spike
- We remove it using mask in the middle of BC1.

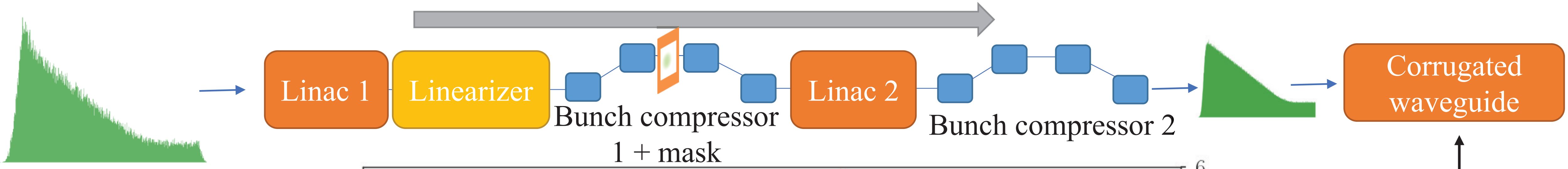


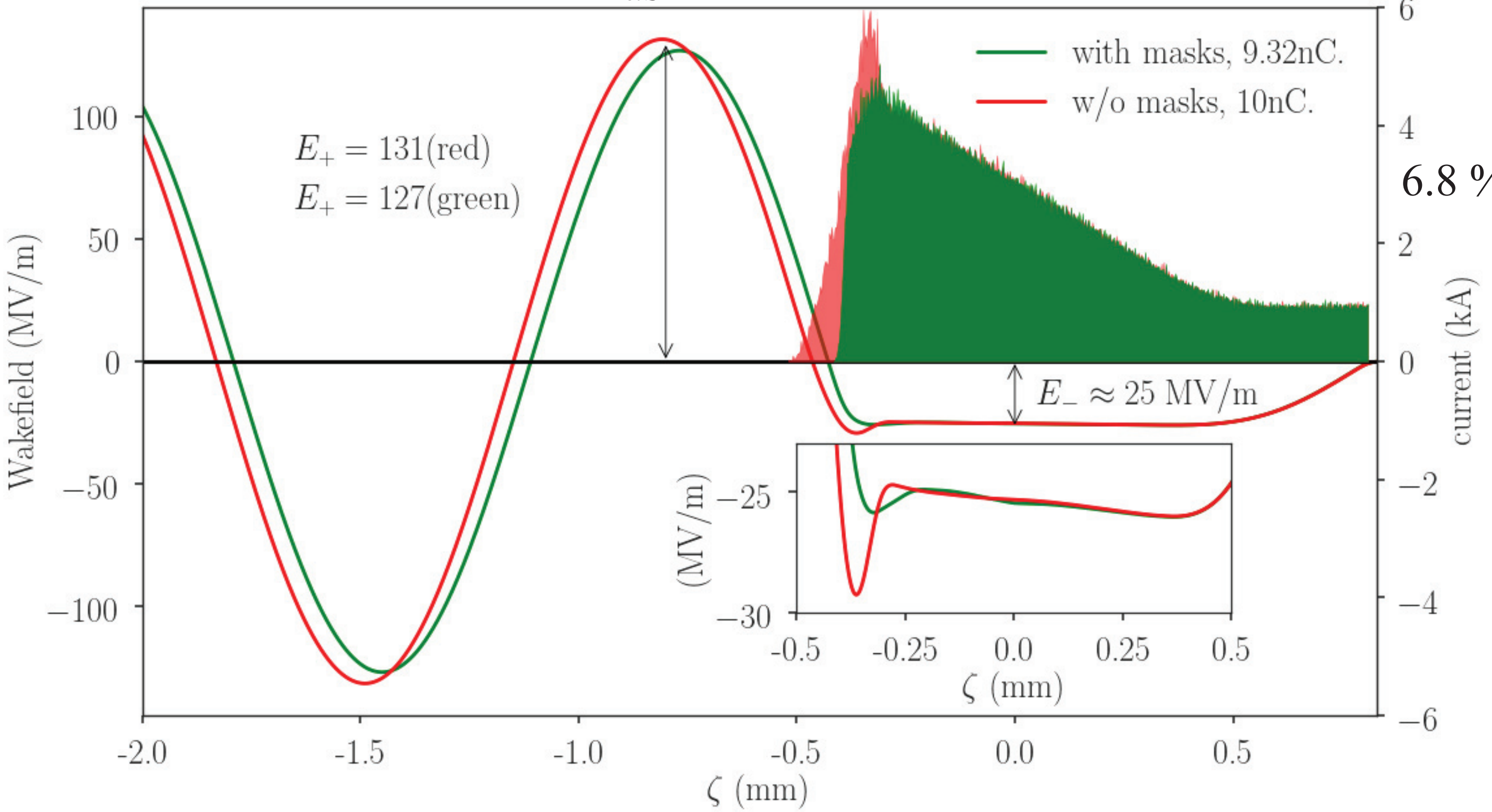
Schematic diagram of the mask
(for illustration purpose only)





Simulation studies – Wakefield generated





6.8 % beam loss after mask

Northern Illinois University

Argonne NATIONAL LABORATORY

Conclusion

- We developed a longitudinal tracking code for forward and backward particle tracking in linacs.
- It includes all known collective effects that were proven to be time reversible.
- For a colinear wakefied accelerator, we defined specific parameters for the drive bunch and and demonstrated that they are obtainable having only a gentle impact of the mask on the beam. (6.8 % beam loss due to the mask)
- Future studies will include:
  - design of the photoinjector producing the initial beam at 60 MeV with required phase space
  - design the BC1 and BC2 to verify the results using a full-fledged particle tracking

Thank you for your attention