ARC-LIKE BUNCH COMPRESSORS FOR WAKEFIELD ACCELERATORS

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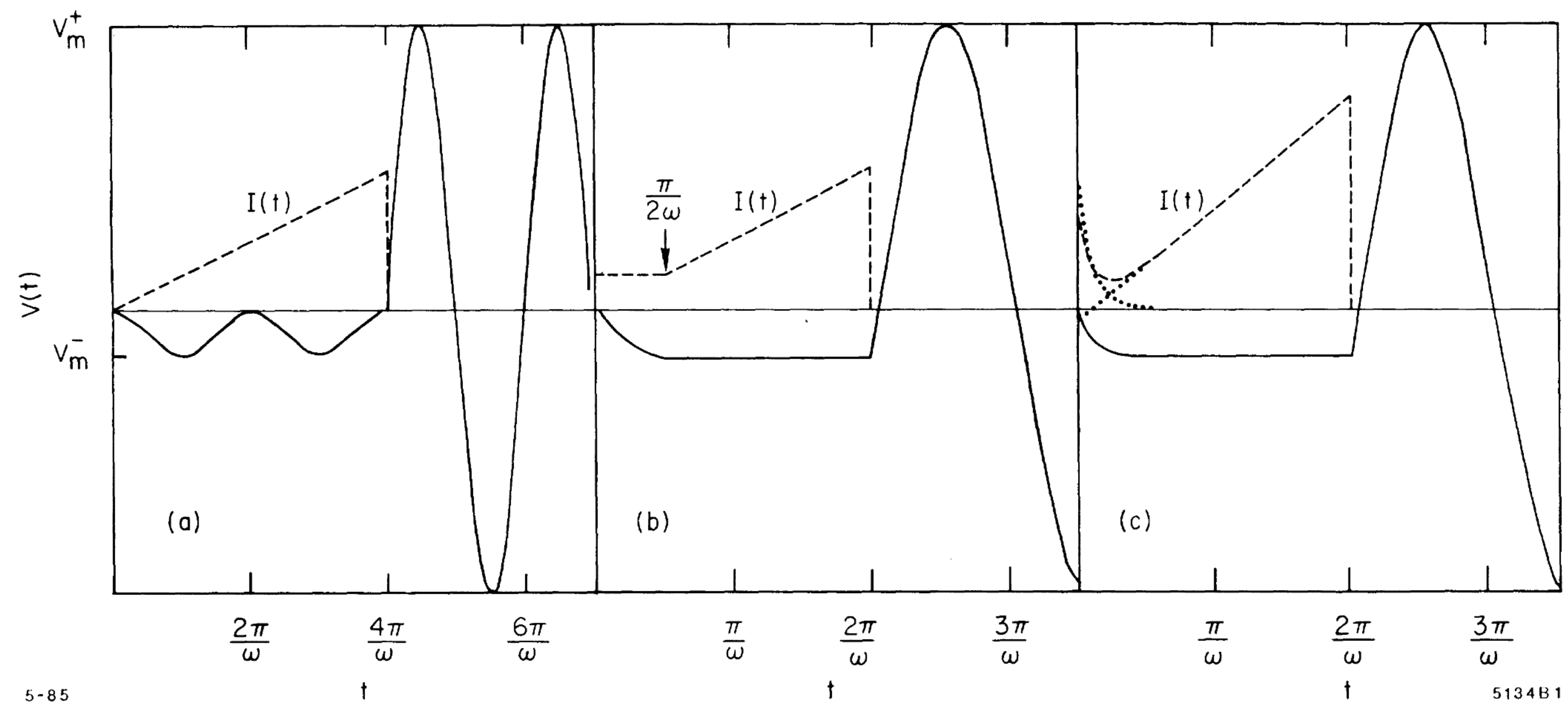
For the sake of getting into the meat and potatoes, I will skip the usual intro spiel

Wakefield Accelerators

WAKEFIELD ACCELERATORS

Two types of wakefield accelerators

- > Non-collinear
  - > Original scheme
  - > Separate propagation axes (CLIC-like)
- > **Collinear**
  - > Same propagation axis
  - > Plasmas and structures



Bane *et al.*, IEEE Trans. Nucl. Sci. **32**, 3524 (1985)

Collinear Wakefield Accelerators

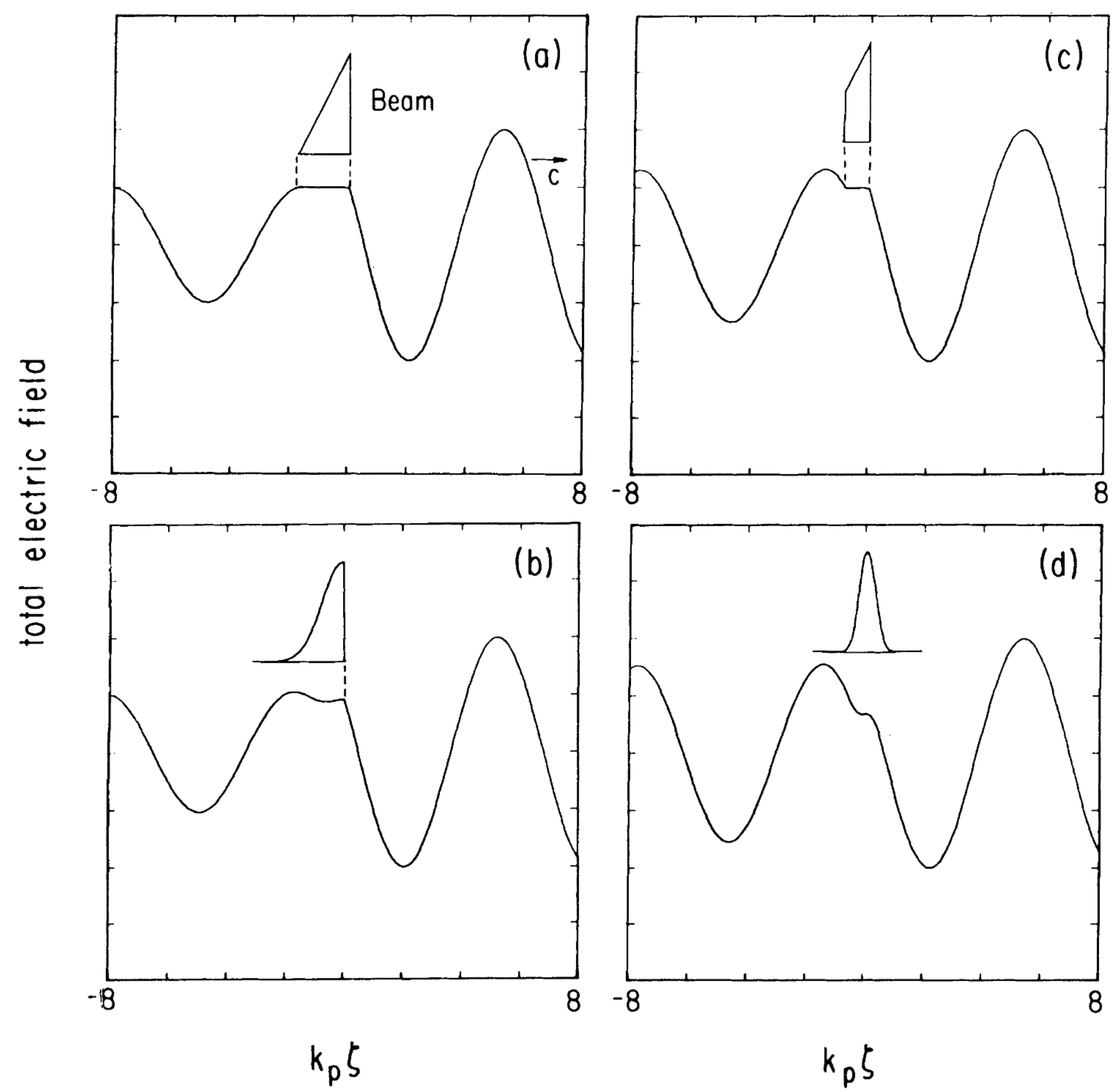
Beam loading essential for any collinear wakefield accelerator

> Linear regime similar for all types

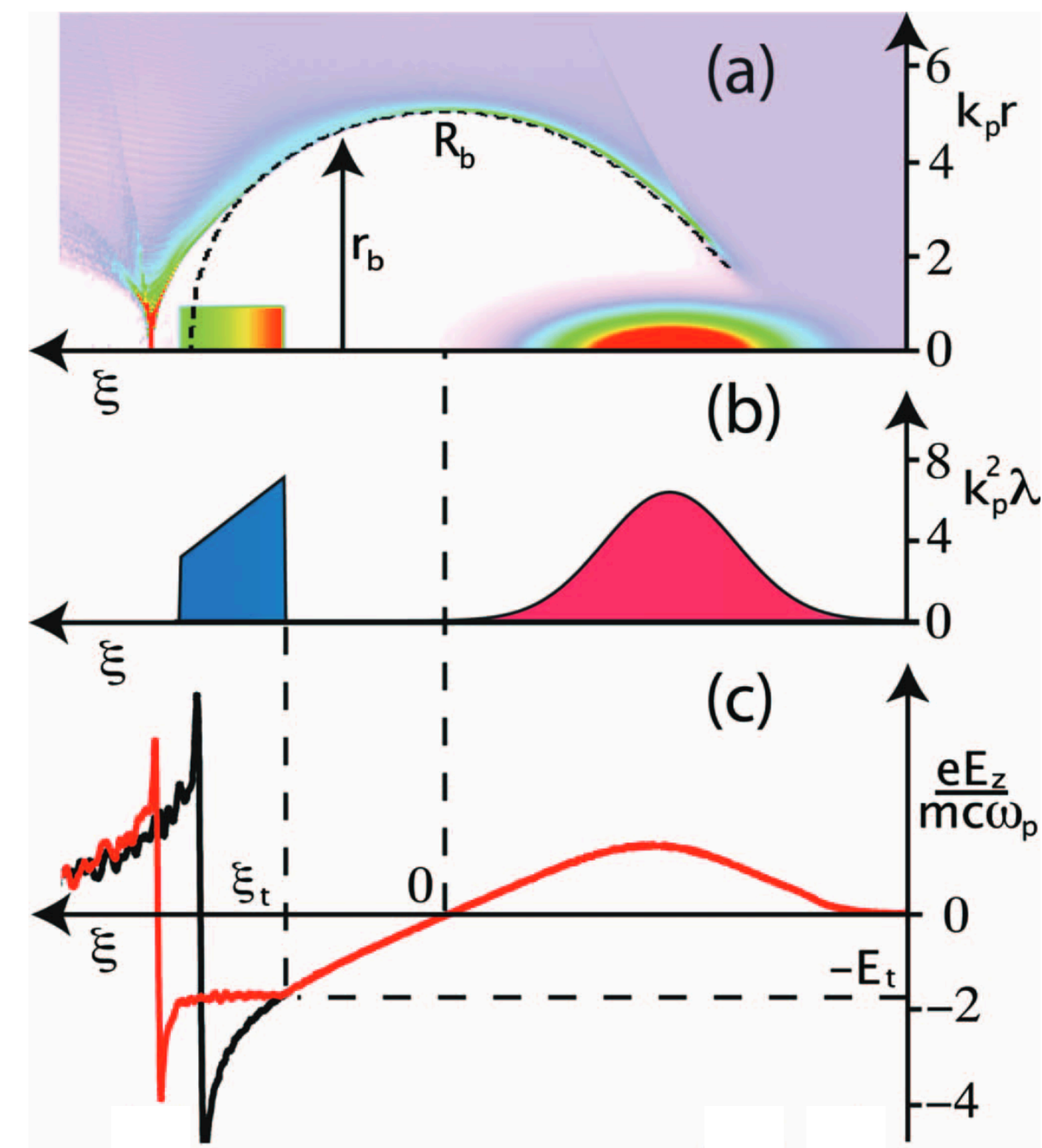
> Nonlinear regime for plasmas

Common feature?

> Linear bunch current ramps!



Katsouleas *et al.*, Particle Accelerators **22**, 81 (1987)



Tzoufras et al., Phys. Plasmas **16**, 056705 (2009)

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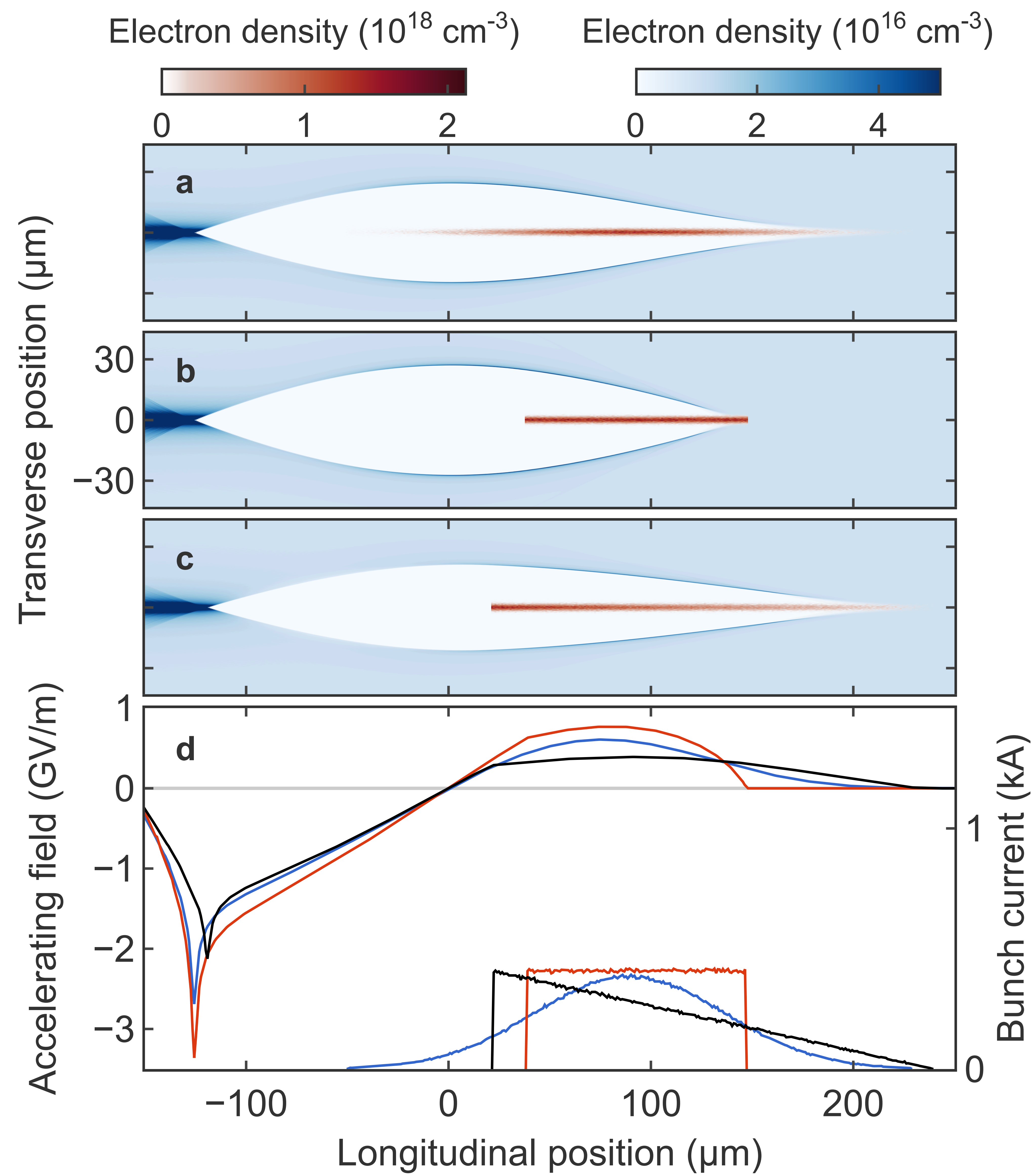


Collinear Wakefield Accelerators

Beam loading essential for any collinear wakefield accelerator

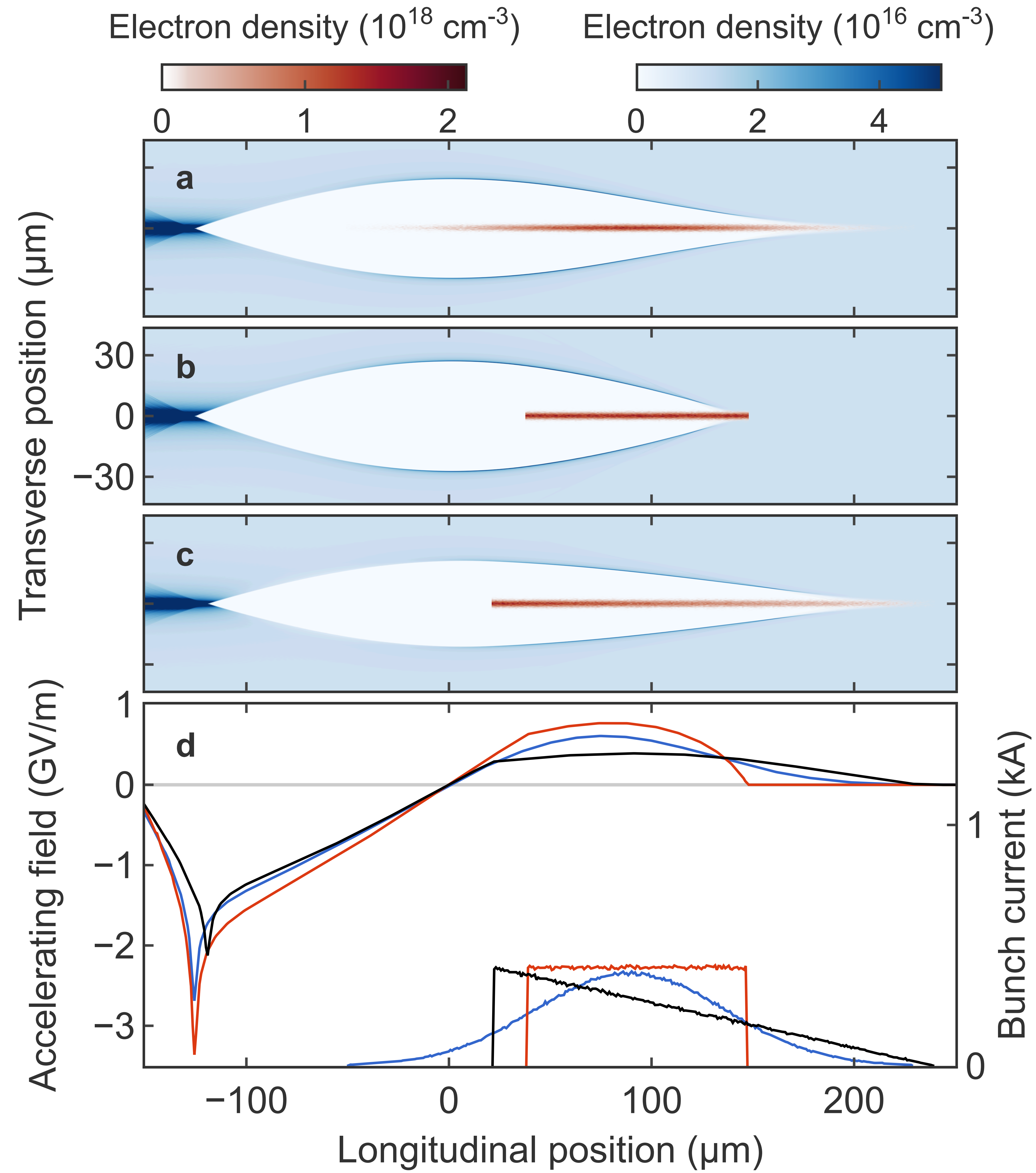
> Linear regime similar for all types

> Nonlinear regime for plasmas

Common feature?

> Linear bunch current ramps!

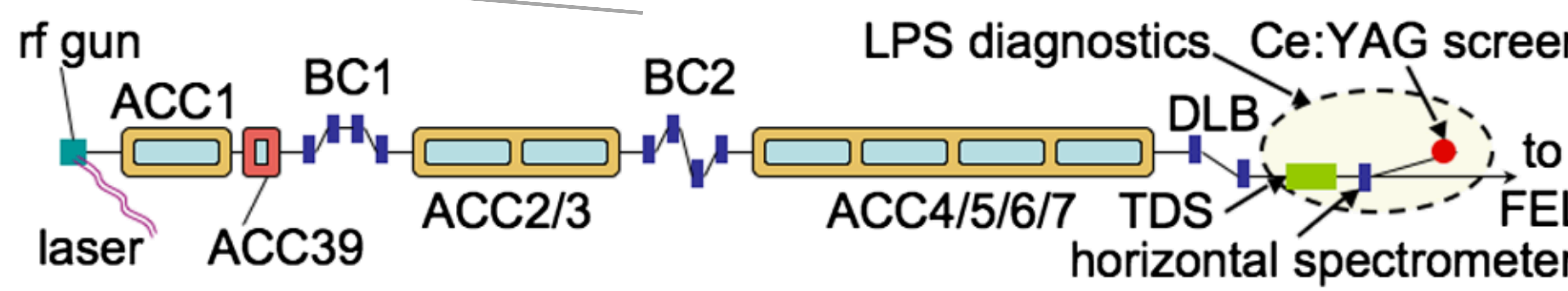
> … but these are not necessarily simple to generate

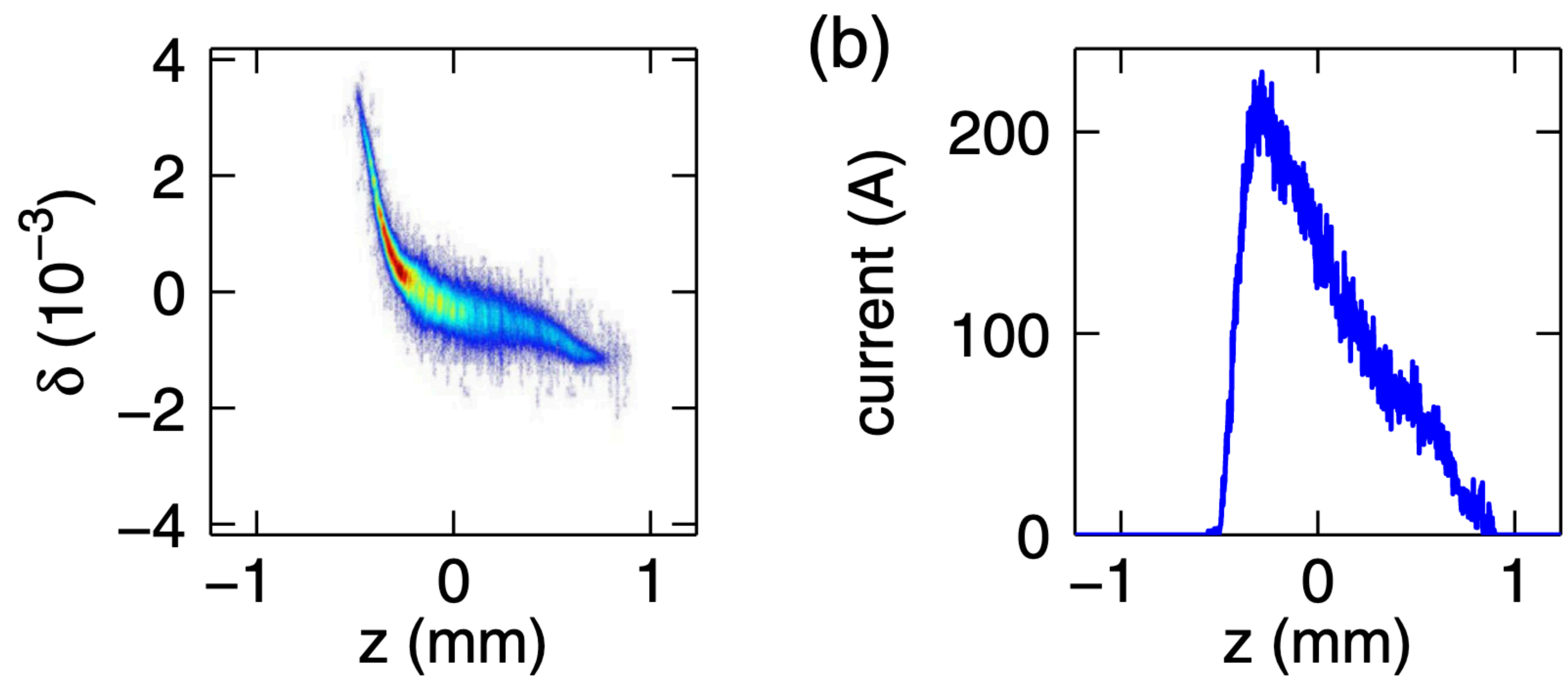


Ramped Current Profiles: Previous Methods

Ramped current profiles have been generated in a number of ways

- **Harmonic cavity w chicanes**
  - Requires double-RF system, limited tuneability





Piot *et al.*, Phys. Rev. Lett. **108**, 034801 (2012)

Ramped Current Profiles: Previous Methods

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- Harmonic cavity w chicanes
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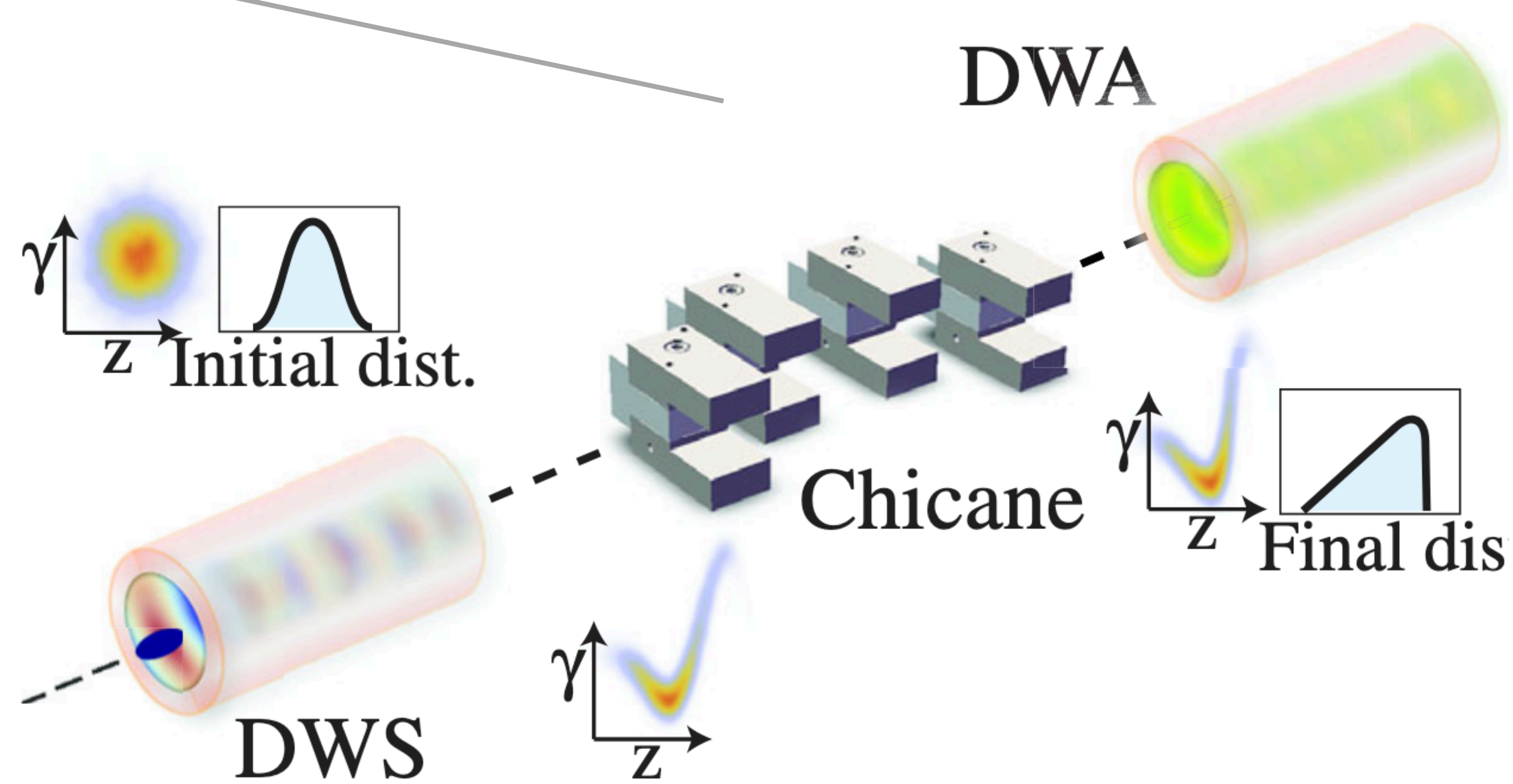
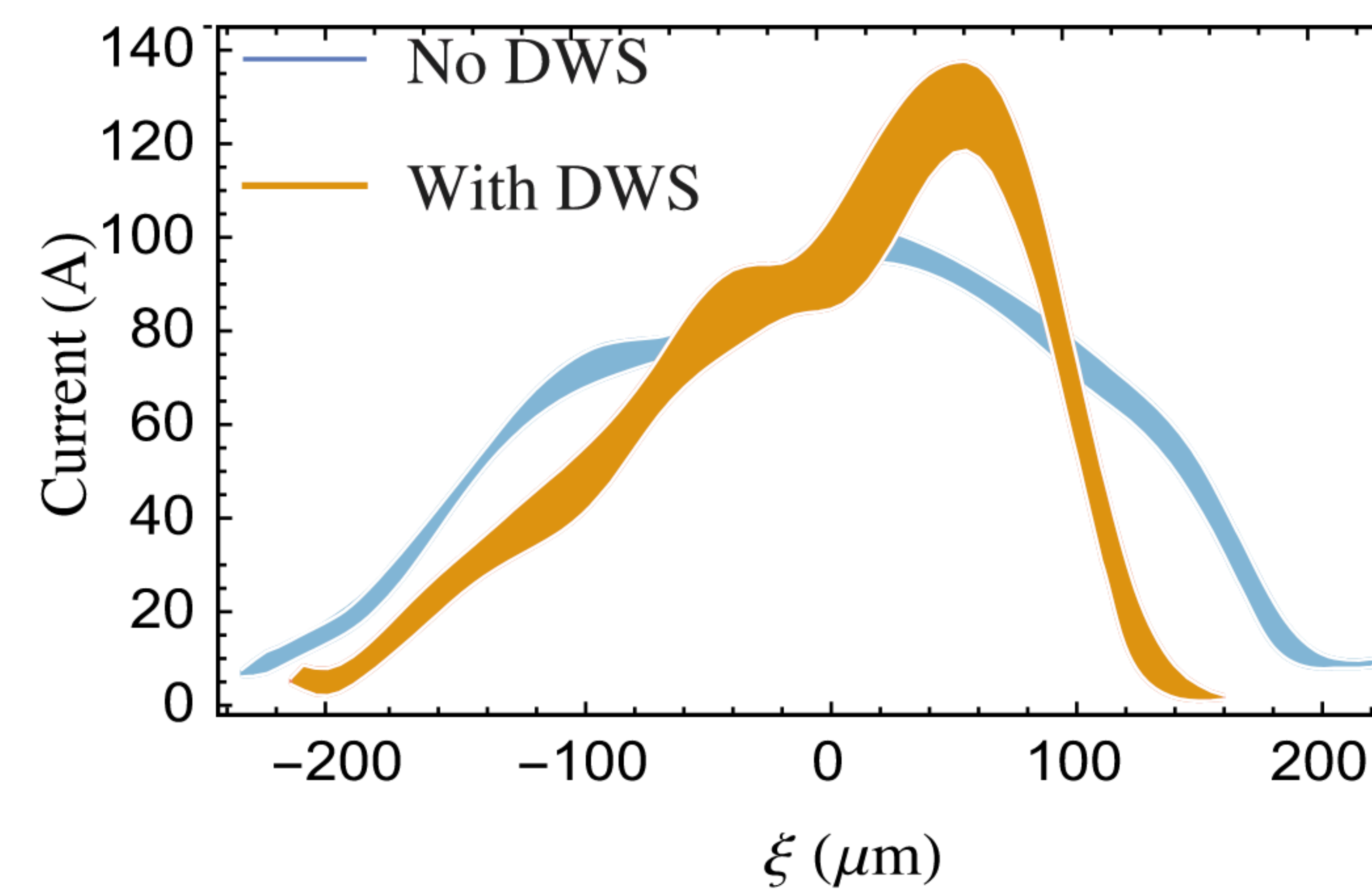
- **Longitudinal wakefields**
  - Limited tuneability





Andonian, *et al.*, Phys. Rev. Lett. **118**, 054802 (2017)

Ramped Current Profiles: Previous Methods

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- Harmonic cavity w chicanes
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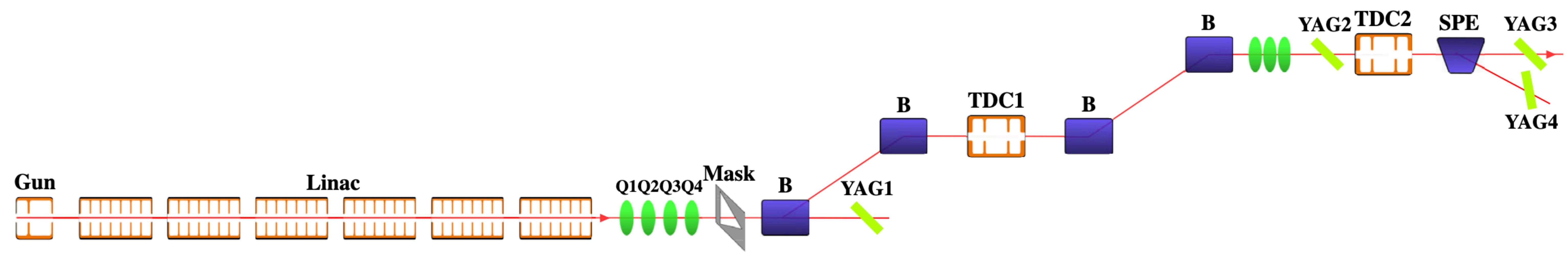
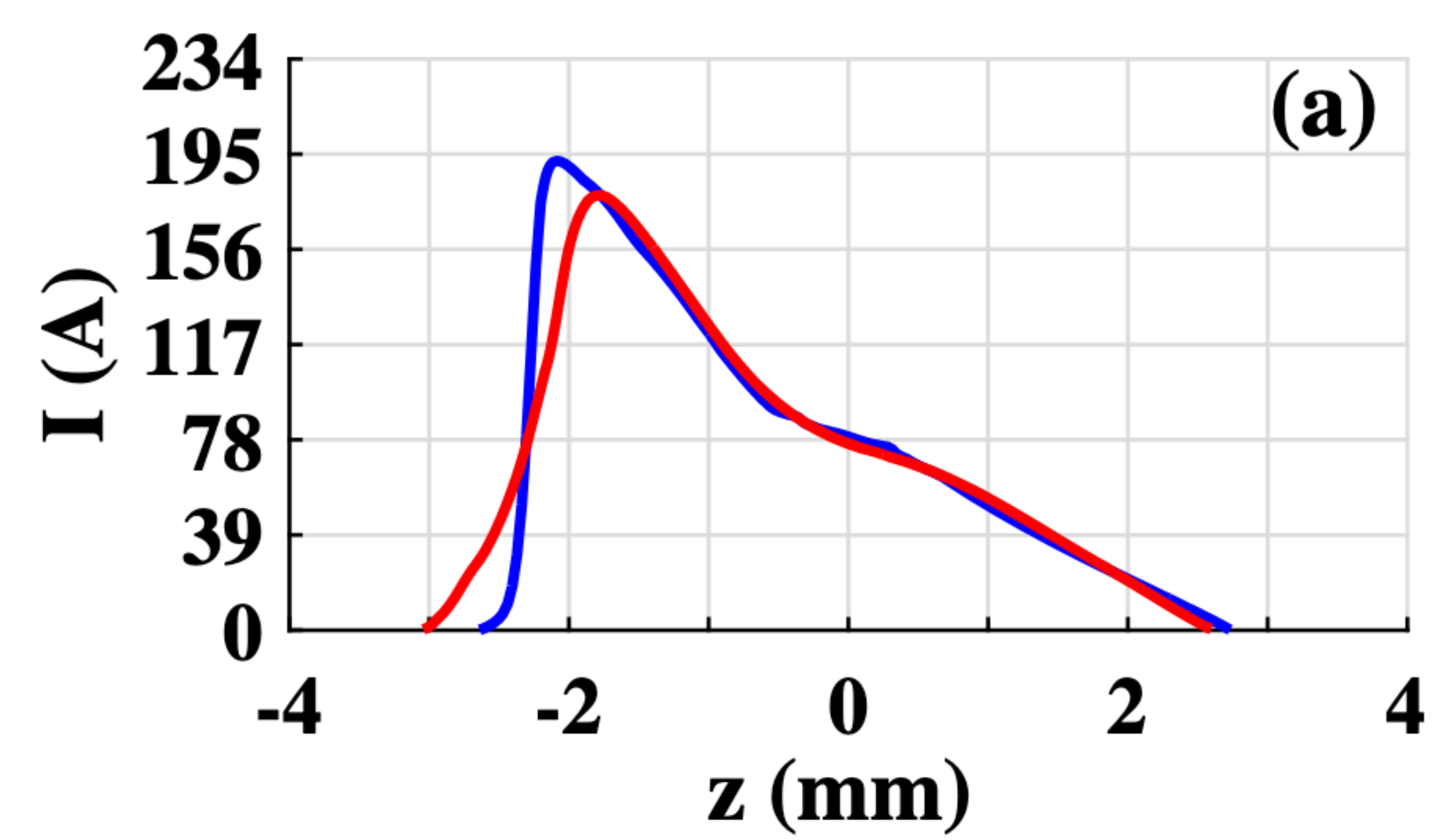
- Longitudinal wakefields
  - Limited tuneability
- **Emittance Exchange**
  - Complex setup, masks/collimators



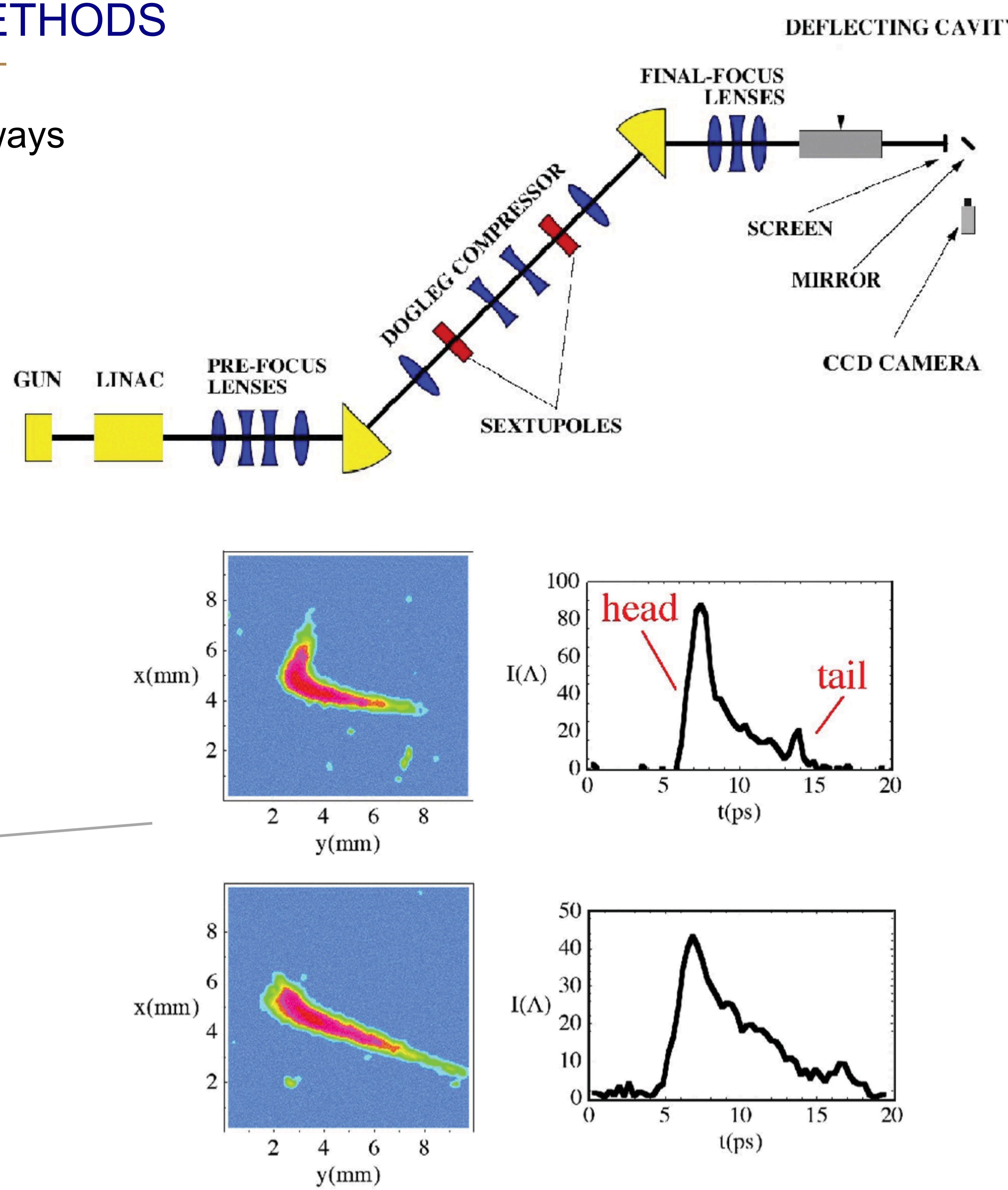


Ha *et al.*, Phys. Rev. Lett. **118**, 104801 (2017)

RAMPED CURRENT PROFILES: PREVIOUS METHODS

Ramped current profiles have been generated in a number of ways

- Harmonic cavity w chicanes
  - Requires double-RF system, limited tuneability
- Longitudinal wakefields
  - Limited tuneability
- Emittance Exchange
  - Complex setup, masks/collimators
- **Nonlinear compression**
  - Nonlinear aberrations - emittance growth



England *et al.*, Phys. Rev. Lett. **100**, 214802 (2008)

Ramped Current Profiles: Previous Methods

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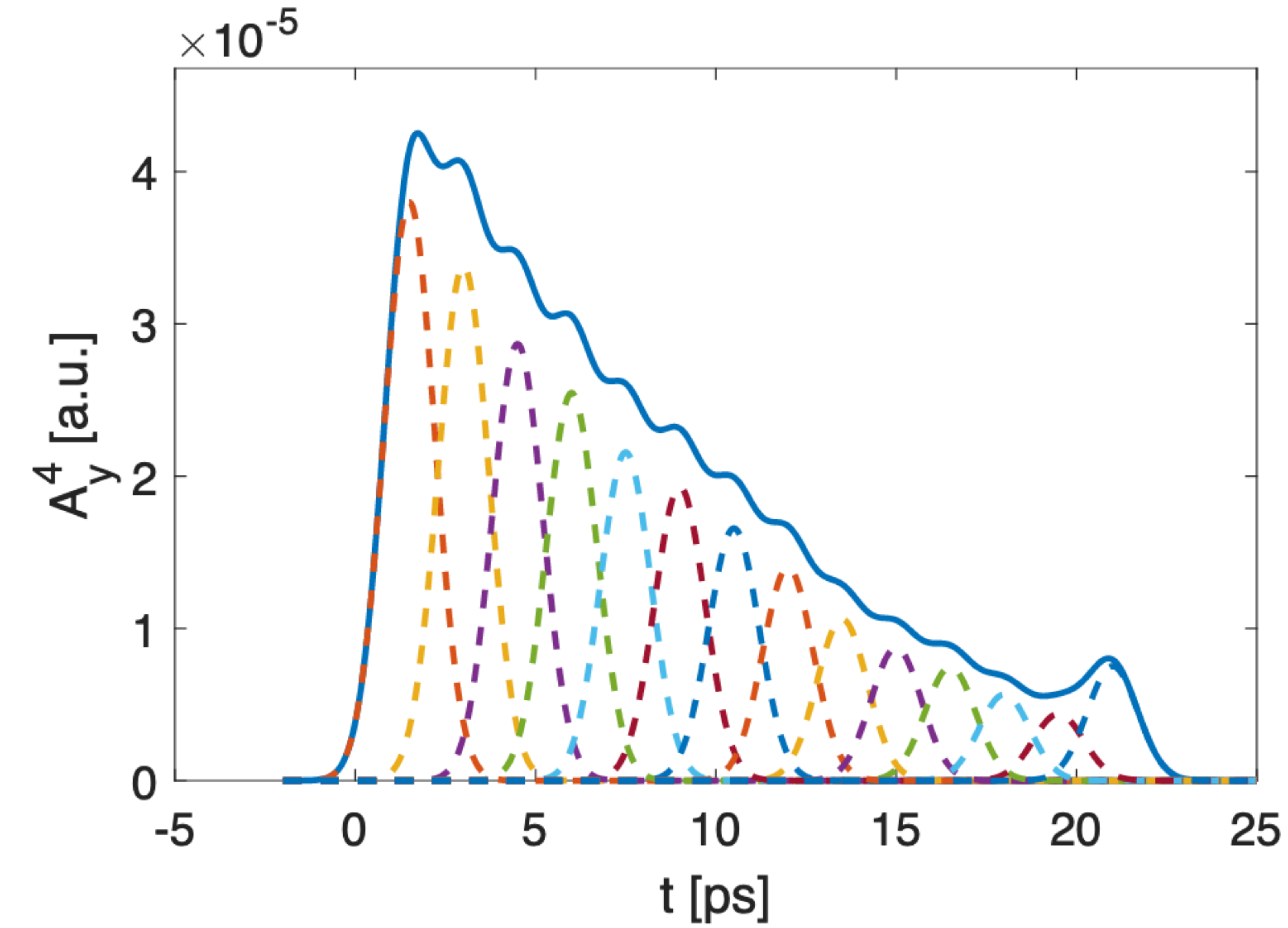
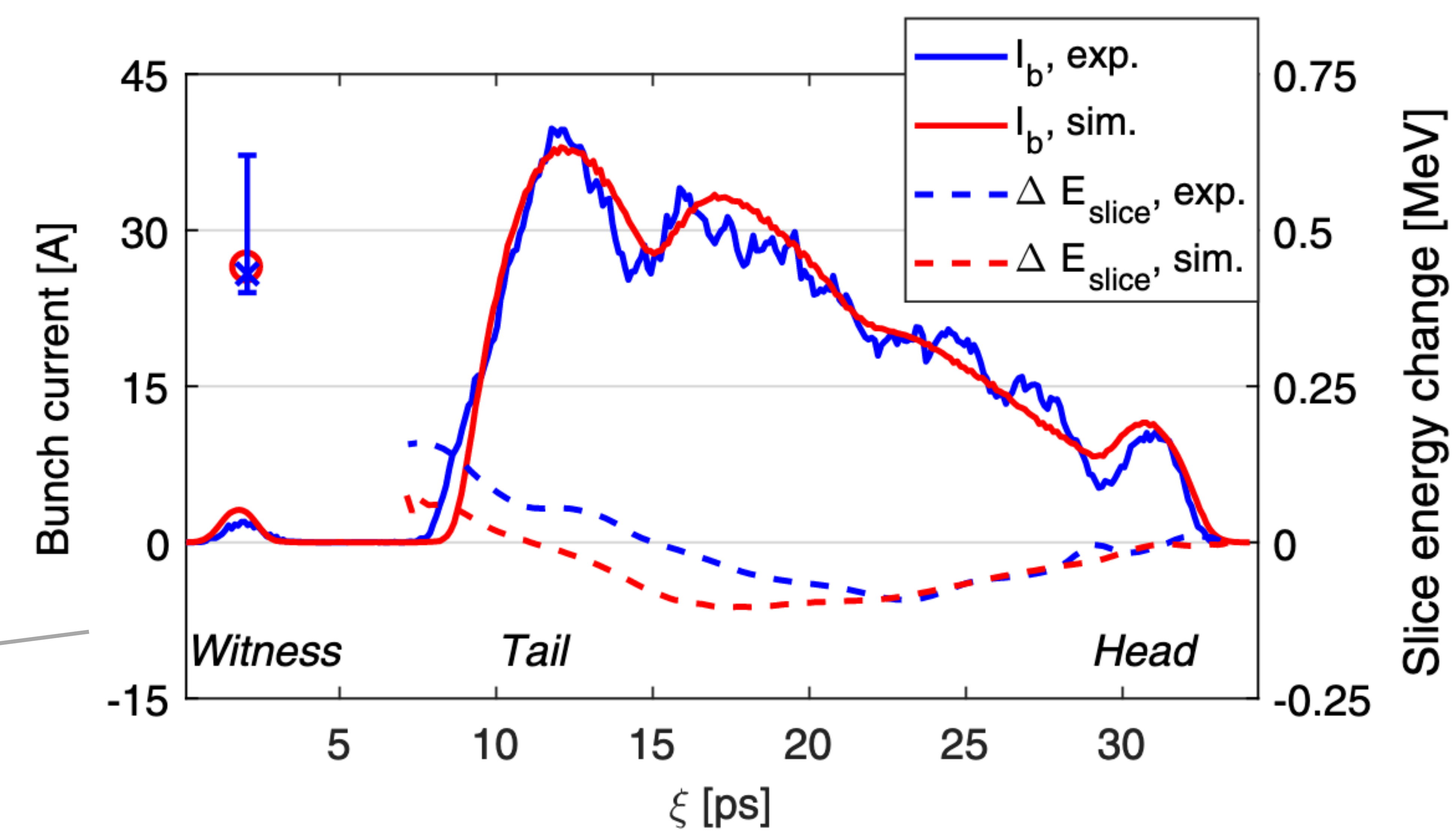
- Longitudinal wakefields
  - Limited tuneability
- Emittance Exchange
  - Complex setup, masks/collimators
- Nonlinear optics
  - Nonlinear aberrations - emittance growth
- **Photocathode laser shaping**
  - Requires specialized laser, bunch compression



G. Loisch, PhD thesis, DESY, 2019



Loisch et al., Phys. Rev. Lett. **121**, 064801 (2018)

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- Longitudinal wakefields
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- Emittance Exchange
  - Complex setup, masks/collimators
- Nonlinear optics
  - Nonlinear aberrations - emittance growth
- Photocathode laser shaping
  - Requires specialized laser, bunch compression

Can we do better?

I think we can!

NONLINEAR BUNCH COMPRESSION, MARK II

Bunch Compression

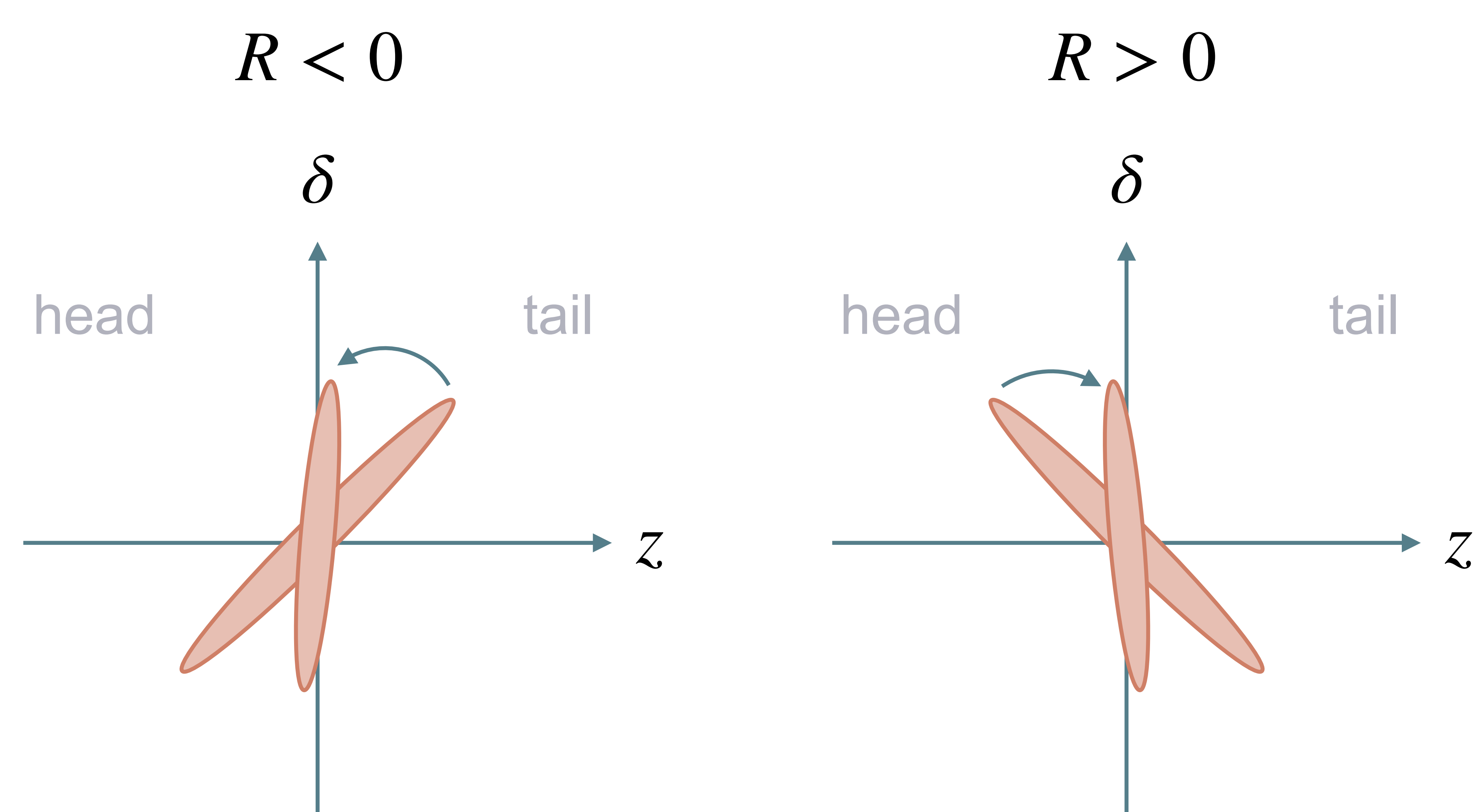
In RF accelerators, bunches start out too long for many applications.
Longitudinal compression decreases duration and increases peak current.

- Usually, longitudinal motion can be described by

$$z_\mathrm{f} = z_\mathrm{i} + R\delta + T\delta^2 + U\delta^3 + \mathcal{O}\left(\delta^4\right)$$

where indices on R, T, and U were dropped for convenience

- Two general types of compression: negative and positive R
  - Rotate LPS in opposite direction



Bunch Compression

Compression is often done with a magnetic structure

> Ultra-relativistic particles - path length differences required

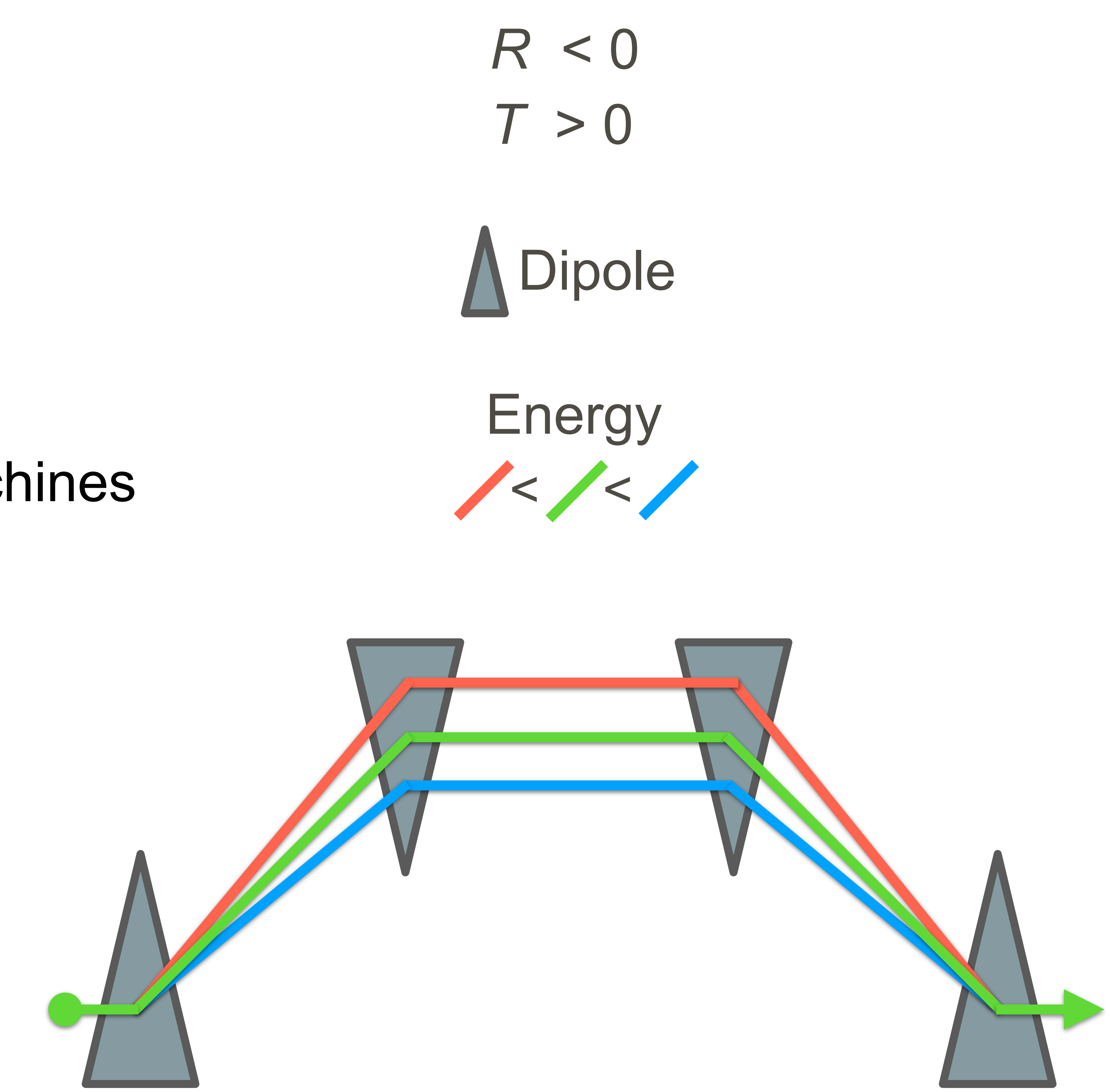
Chicanes are the most common bunch compressor in high-energy machines

> Simple geometry. Higher-energy particles take a *shortcut*, lower-energy particles a detour: $R < 0$

> Fixed dispersion relations: $T \approx -3/2R$, $U \approx 2R$

> Higher-frequency RF

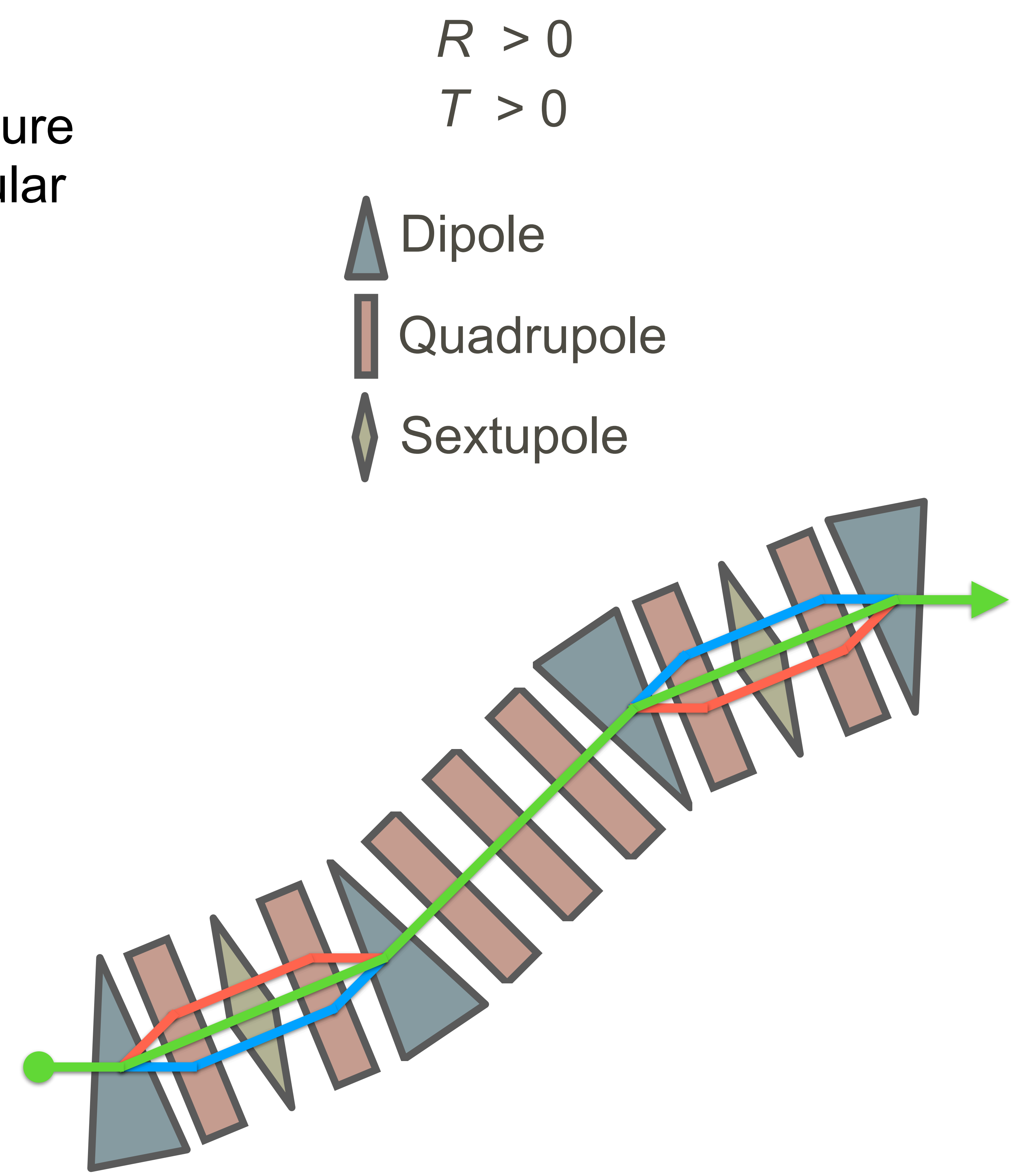
> Limited optics control



Bunch Compression

Other methods investigated over the years, but chicanes were simple and well-understood.

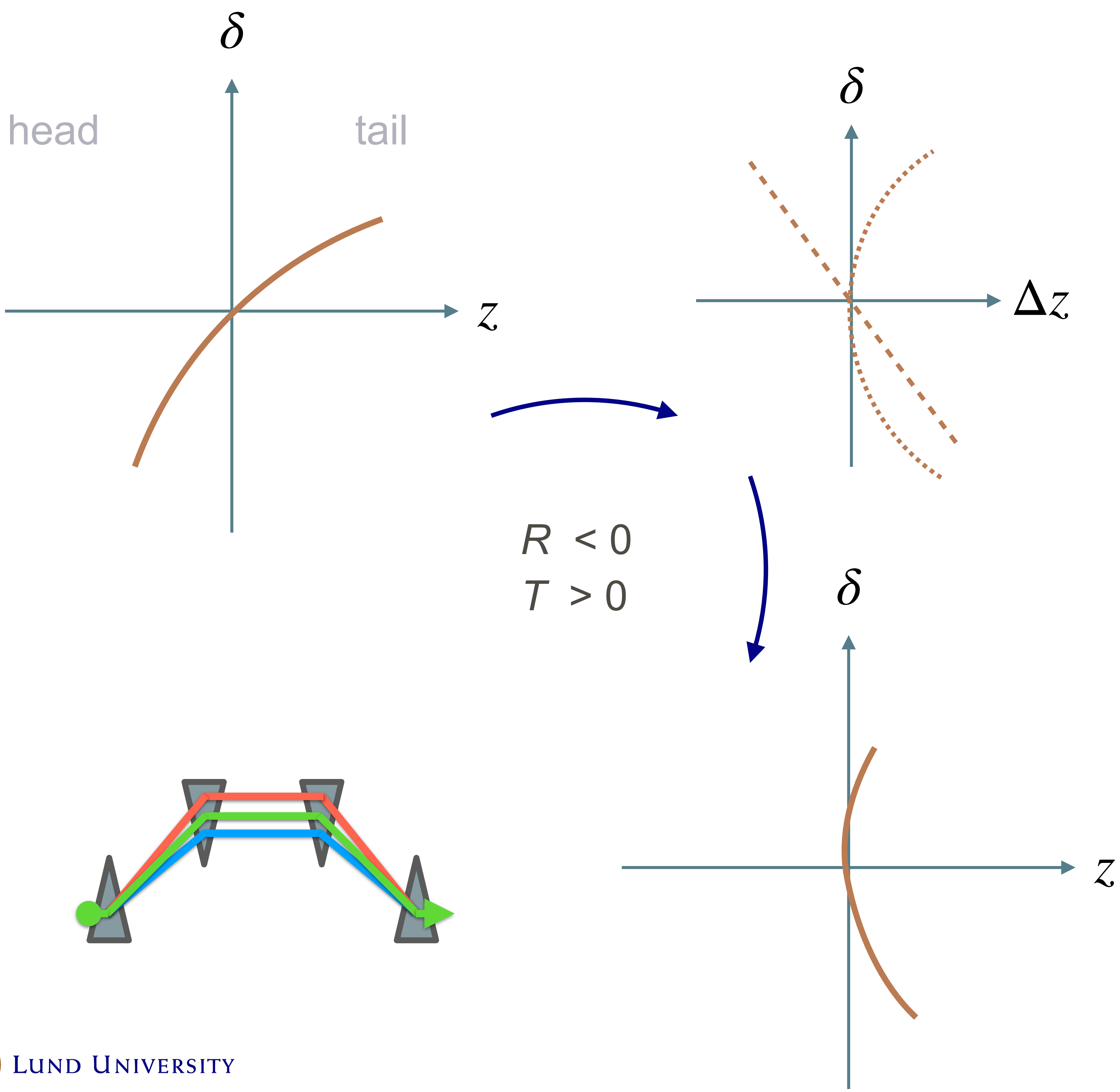
When designing MAX IV, there was no budget for a double-RF infrastructure or the staff to maintain it. They borrowed the achromat concept from circular machines for the bunch compressors instead.

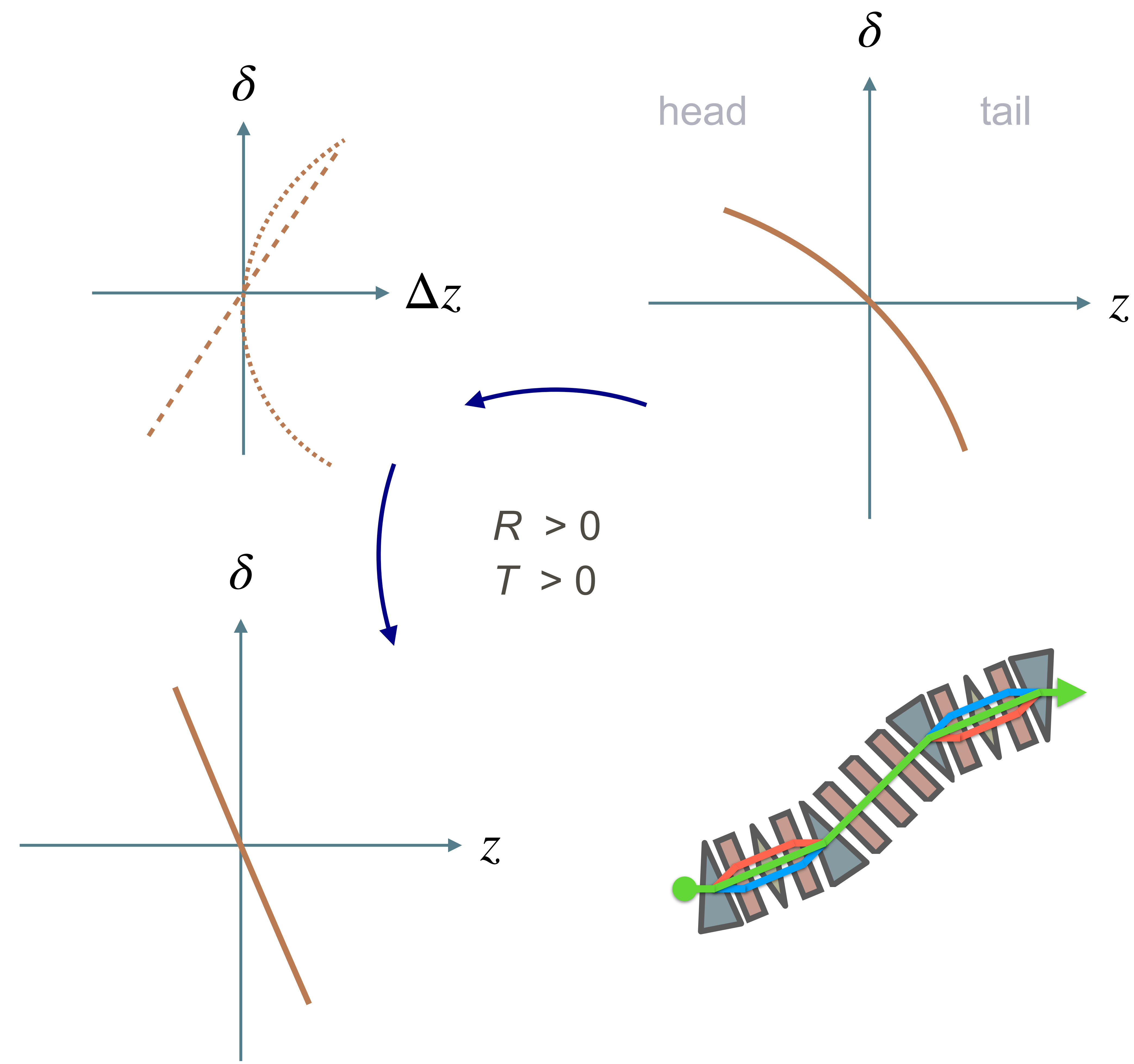


- More complex geometry. higher-energy particles take a detour, lower-energy particles a *shortcut:* $R > 0$
- Optical/passive linearization, single-RF sufficient ($R, T > 0$)
- Dispersion relations tunable with magnets
- Significant optics control

Bunch Compression

Different phase space linearization techniques





Bunch Compression

Different phase space linearization techniques

$$\Delta z = R\delta + T\delta^2 + U\delta^3 + \mathcal{O}(\delta^4)$$

> Chicane: alter accelerating field
>> Harmonic RF cavity

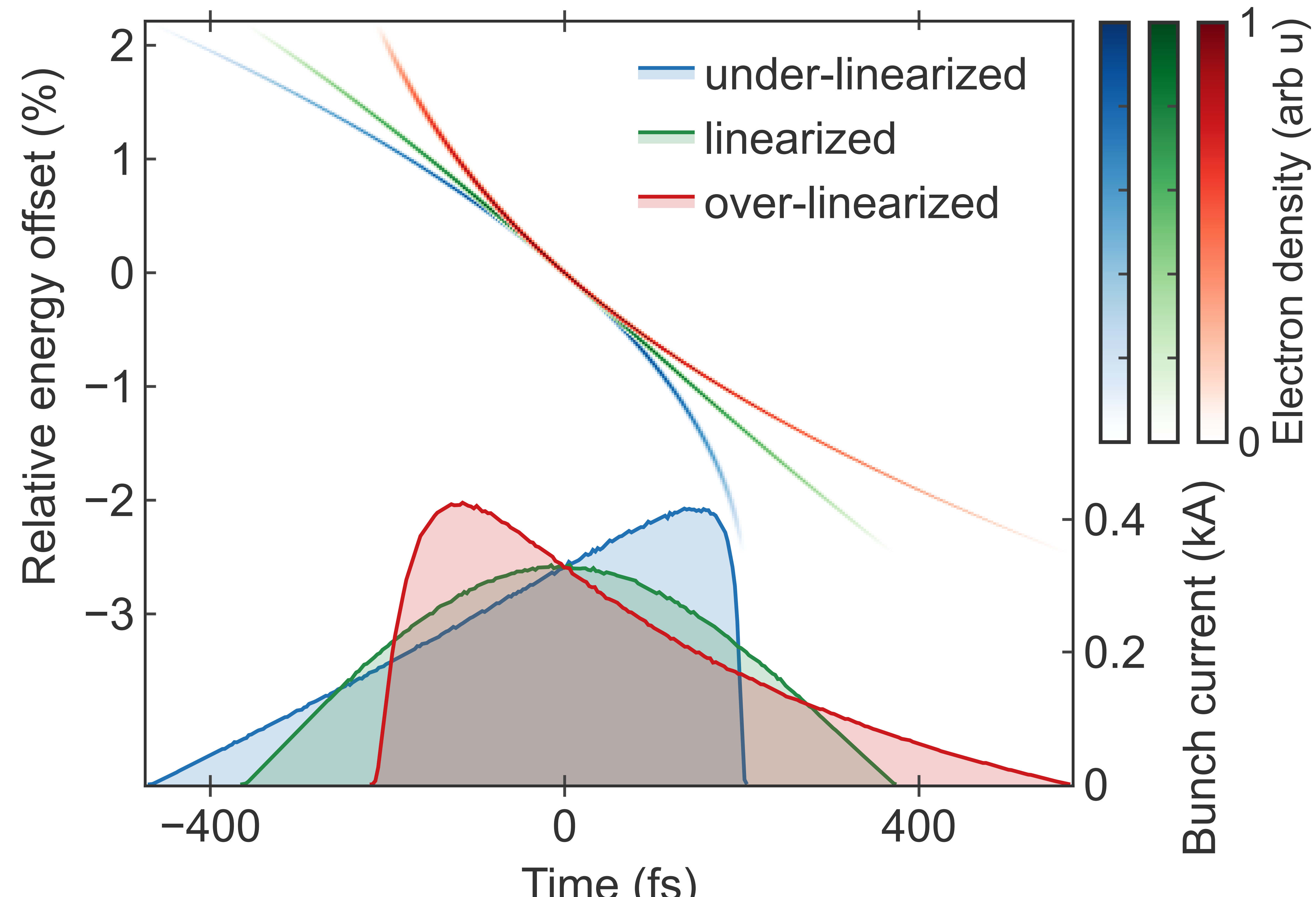
> Arc-like: alter bunch compressor
>> Sextupoles (+higher orders)

Only when sign(R) = sign(T) can LPS linearization be controlled optically/passively!

Bunch Compression

Different phase space linearization techniques

- Chicane: alter accelerating field
  - Harmonic RF cavity
- Arc-like: alter bunch compressor
  - Sextupoles (+higher orders)

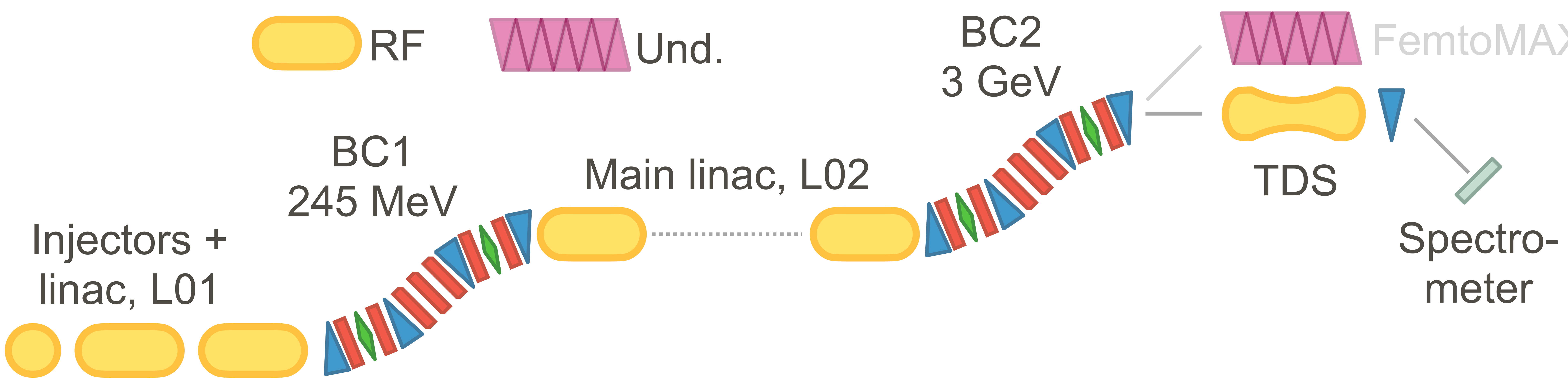


Experimental Results from MAX IV

Experimental Results from MAX IV

Experiment set up in the diagnostic beamline at the MAX IV linac

- Mild compression in both BCs
- Measured LPSs on TDS spectrometer screen



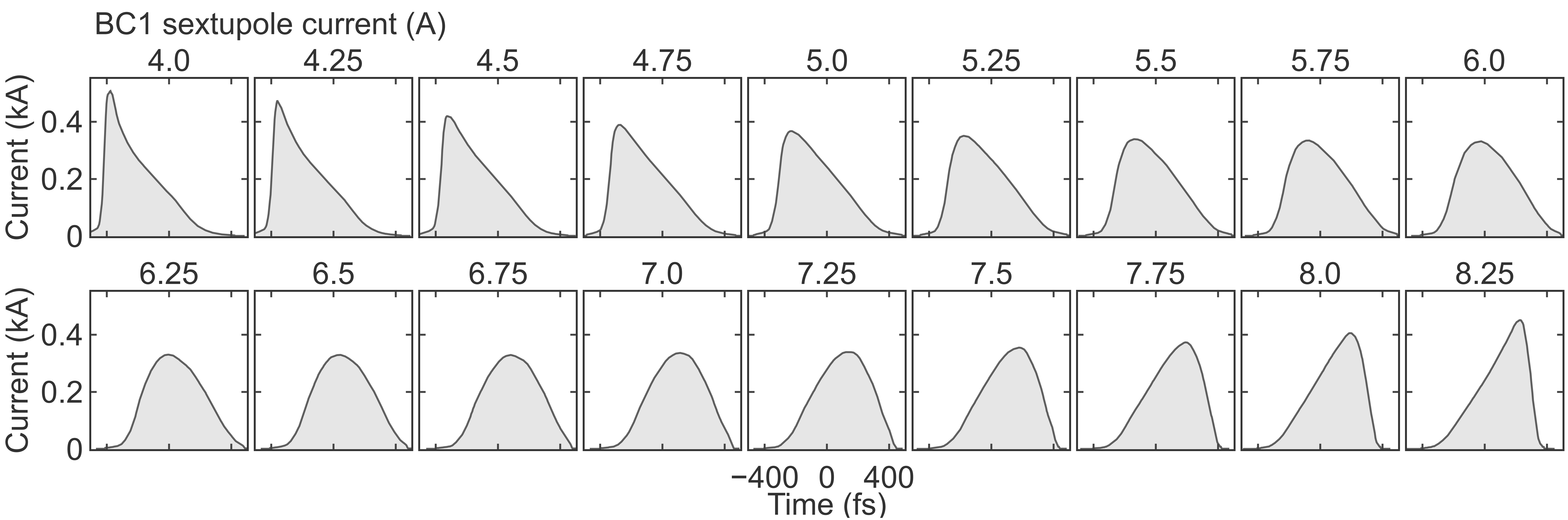
Experimental Results from MAX IV

Experiment set up in the diagnostic beamline at the MAX IV linac

> Mild compression in both BCs

> Measured LPSs on TDS spectrometer screen

> Scanned BC1 sextupoles from (nearly) min to max at both TDS ZCs



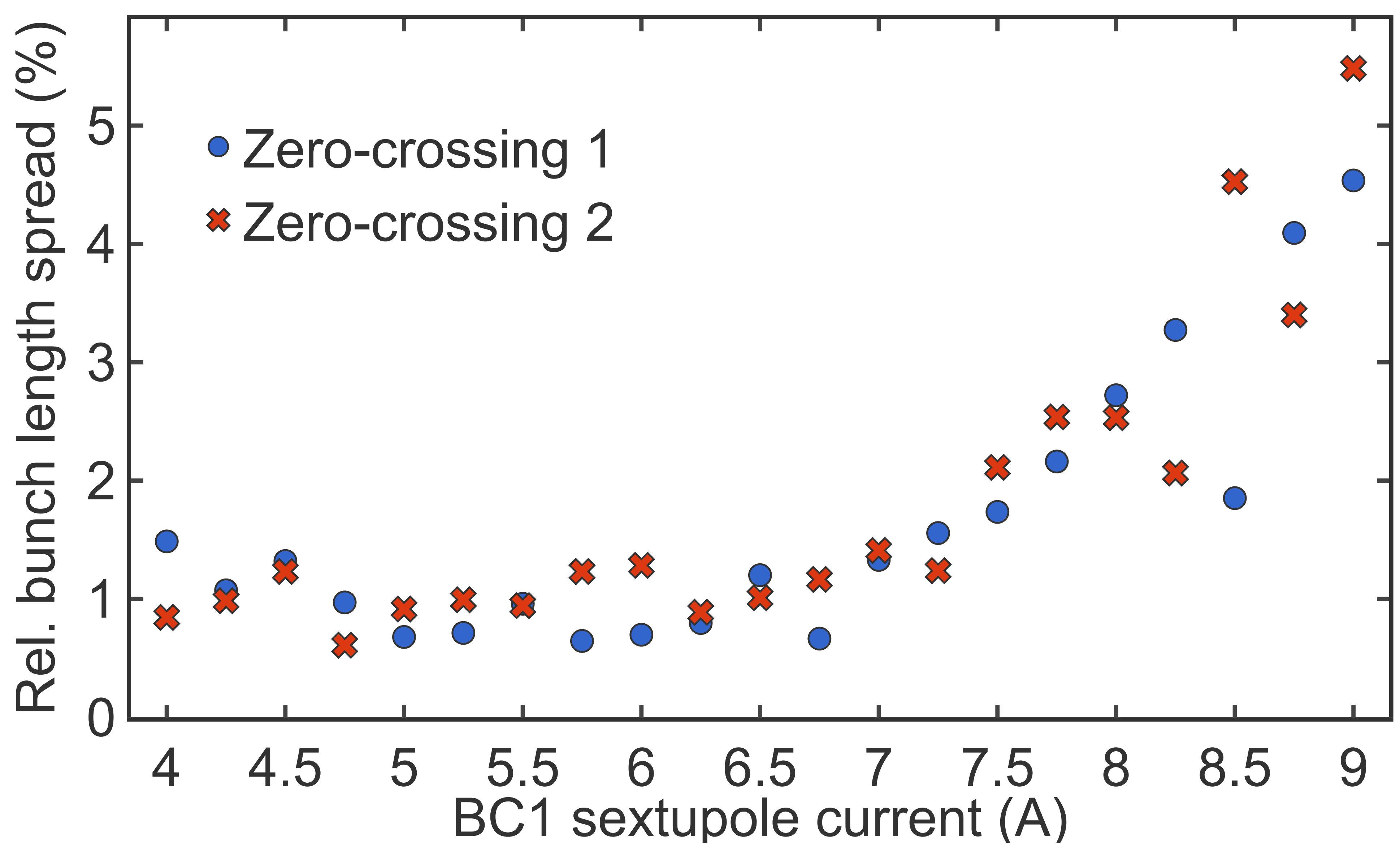
MITIGATING BUNCH COMPRESSION JITTER

Bunch Compression Jitter

Interesting feature in the ramped current profile data

> *Spread* in bunch lengths also varied with SX strength

> Led to a deeper dive in nonlinear compression dynamics



BUNCH COMPRESSION JITTER

It turns out that nonlinear compression is important in several ways

> Linear compression factor

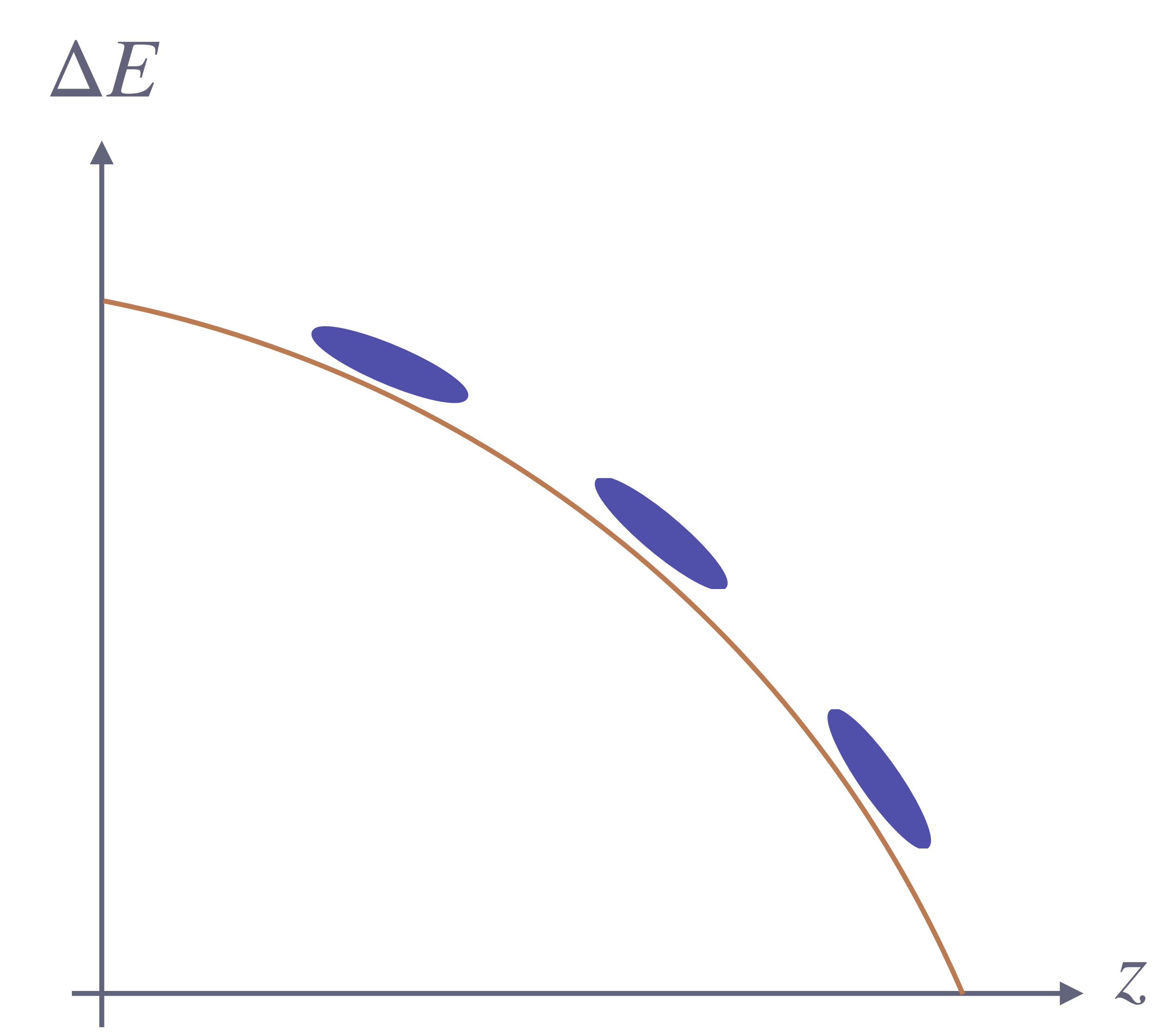
$$C_0 = \frac{1}{1 + hR}$$

> When RF varies, energy and chirp change in a correlated way

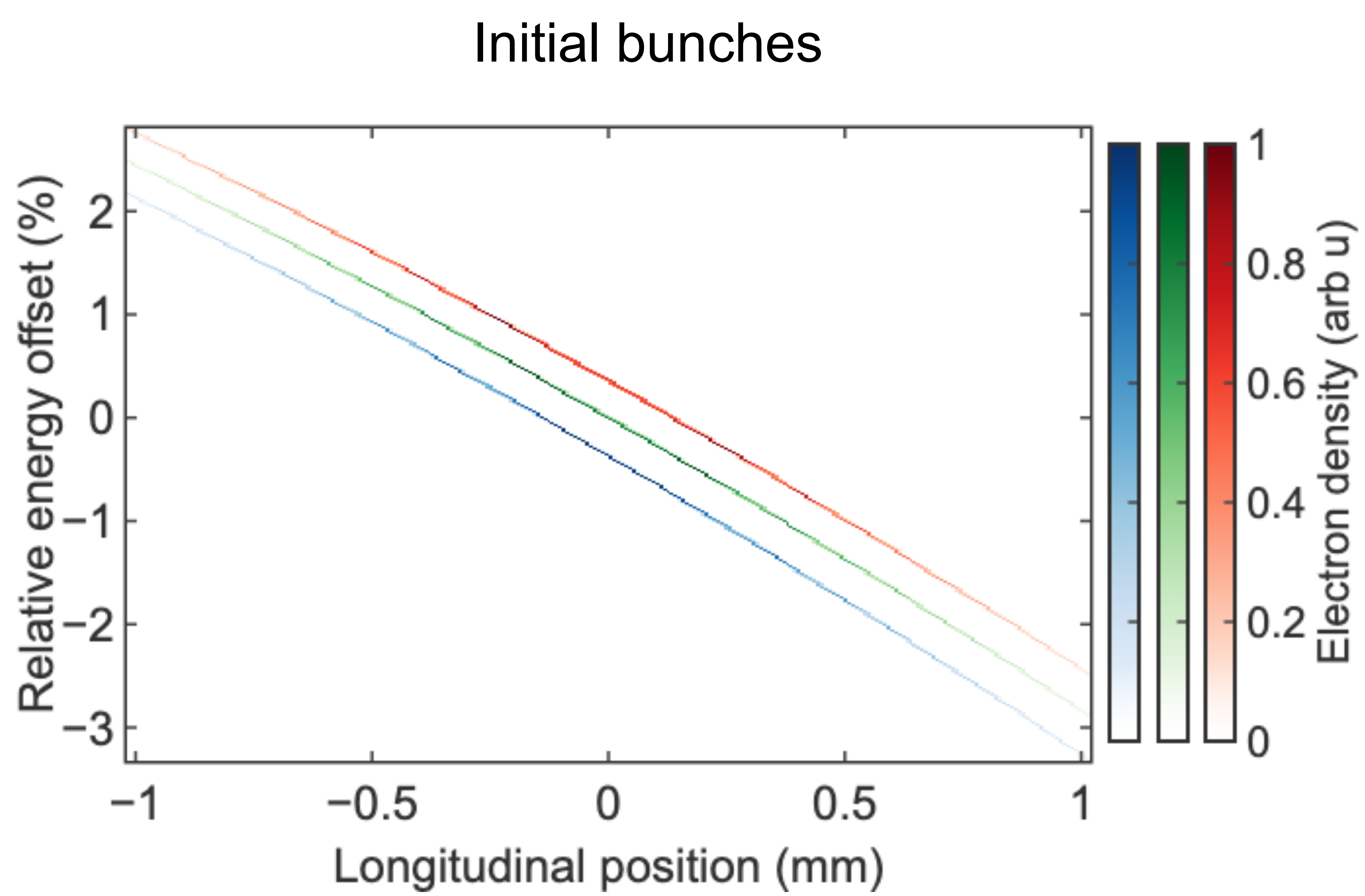
  > Example: when phase moves closer to crest, energy goes up but chirp h goes down, and vice versa

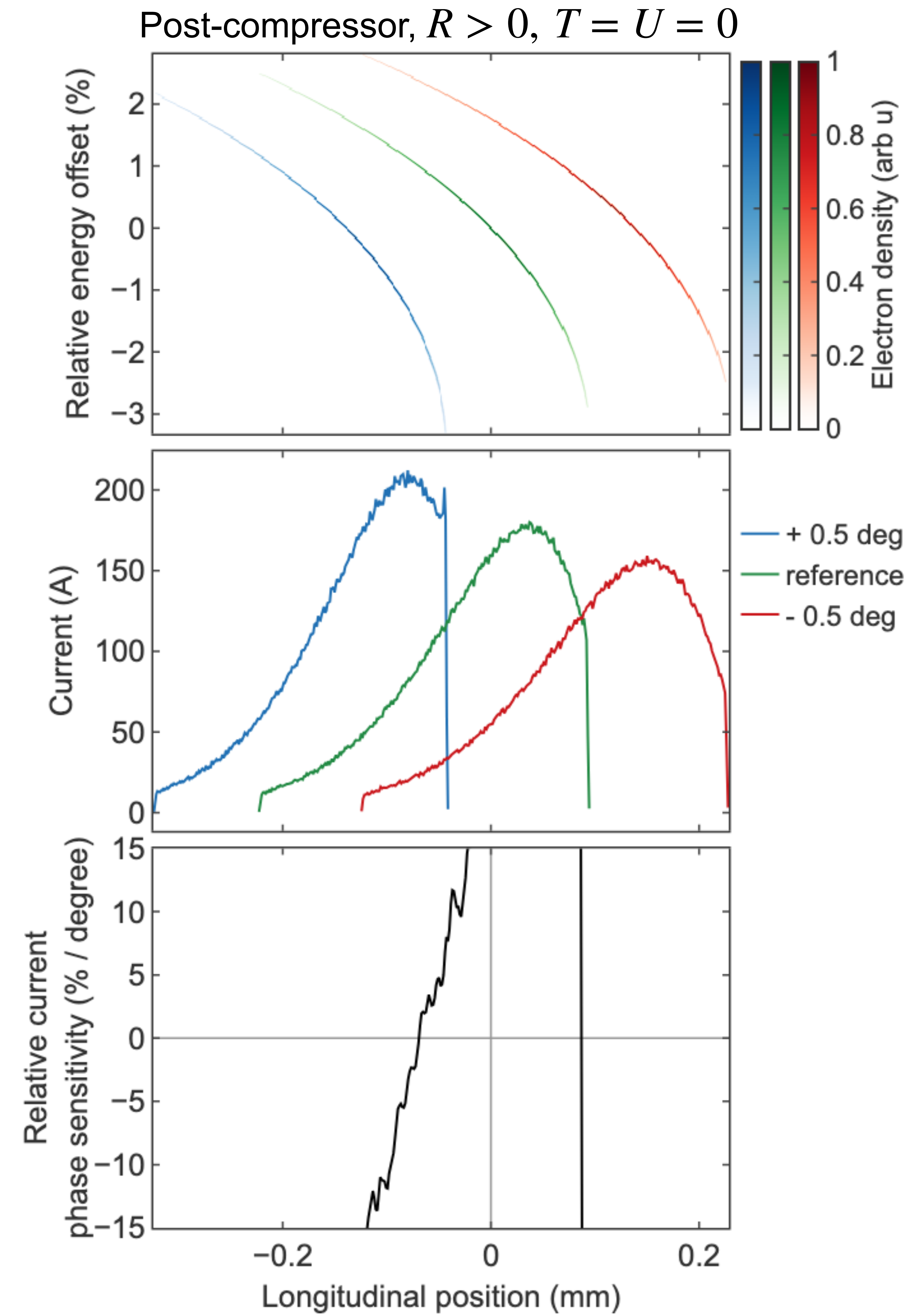
  > Normally leads to compression jitter

  > If R could change opposite h, variations could cancel out



Bunch Compression Jitter





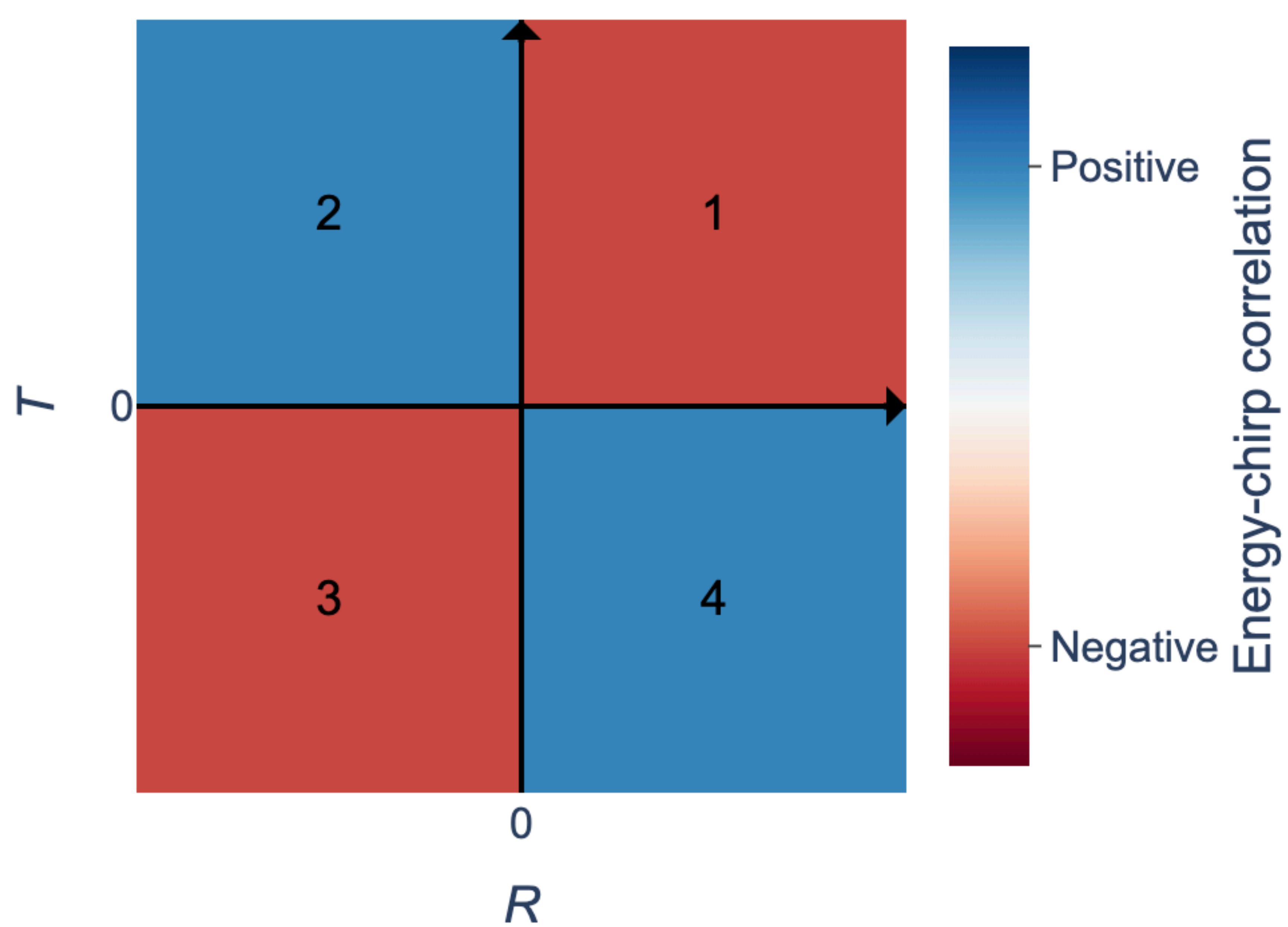
Bunch Compression Jitter

It turns out that nonlinear compression is important in several ways

- Nonlinear compression factor

$$z_{\mathrm{f}} = z_{\mathrm{i}} + R\delta + T\delta^2 + U\delta^3 + \mathcal{O}\left(\delta^4\right) \quad \rightarrow \quad C \equiv \frac{1}{\frac{\mathrm{d}z_{\mathrm{f}}}{\mathrm{d}z_{\mathrm{i}}}} = \frac{1}{1 + h\left(R + 2T\delta + 3U\delta^2 + \mathcal{O}\left(\delta^3\right)\right)}$$

  - The *effective* R that the beam "sees" varies with δ through primarily T
  - Example: for RF phase variation, if energy goes up, chirp goes down, so we must have $\operatorname{sign}(R) = \operatorname{sign}(T)$
    - This is the case for typical arc-like compressors
    - Not for chicanes!



BUNCH COMPRESSION JITTER

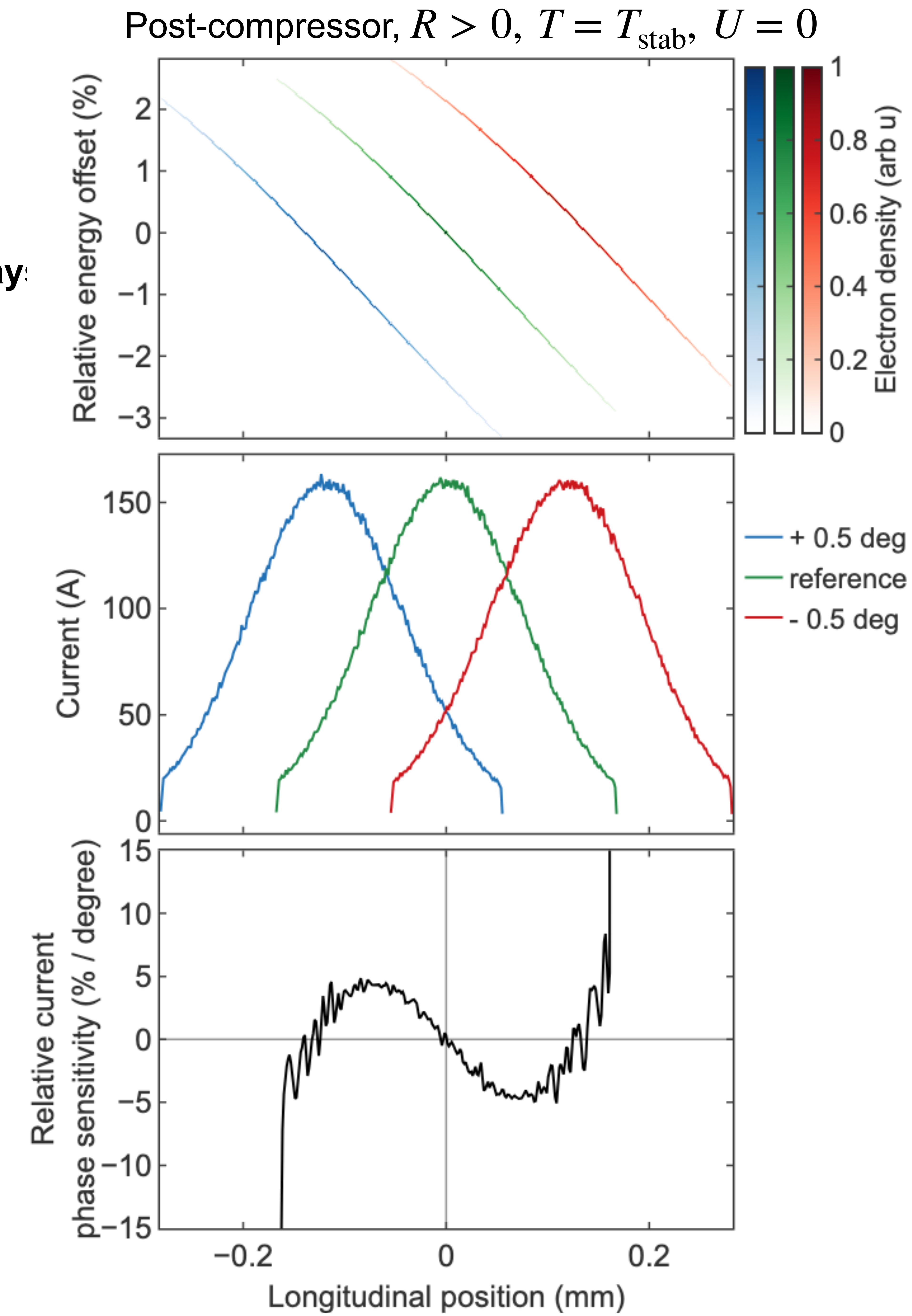
It turns out that nonlinear compression is important in several way

> A bit more rigorous…

$$\left.\frac{\partial_\phi C}{C_0}\right|_{z=0} = \frac{A}{\mathscr{E}_0}\left[C_0 Rk\cos(\phi) - 2(C_0-1)\frac{T}{R}\sin(\phi)\right]$$

> Phase-jitter-induced compression jitter eliminated when

$$T_{\mathrm{stab}} = \frac{R^2}{2}\frac{C_0}{C_0-1}\frac{k}{\tan(\phi)} = \frac{R}{2}\frac{\mathscr{E}_0}{\Delta\mathscr{E}}\frac{1}{\tan^2(\phi)}$$



Bunch Compression Jitter

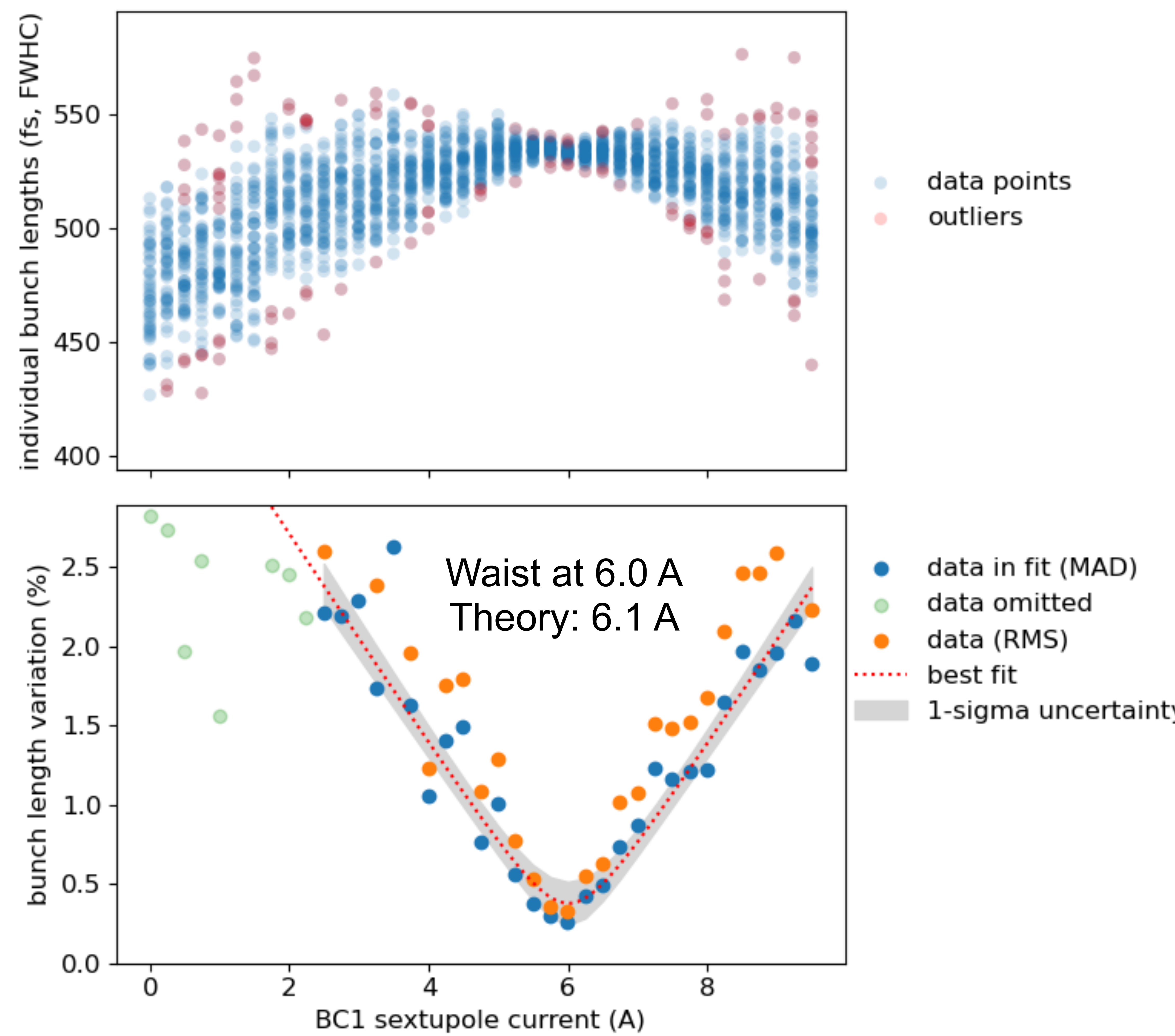
Experimental results from MAX IV

> Off-crest into BC1, opposite side of crest after to eliminate chirp before BC2
>
> > Isolates BC1

> Scan sextupoles (T (and U))

> Measure bunch lengths on TDC (both ZCs)
>
> > 50 shots per step
> >
> > Robust bunch length metric
> >
> > > Full-width-half-charge (rebranded IQR)
> >
> > Get width of bunch-length distribution
> >
> > > MAD (full) and RMS (filtered)

22 degrees off-crest before BC1, ZC2

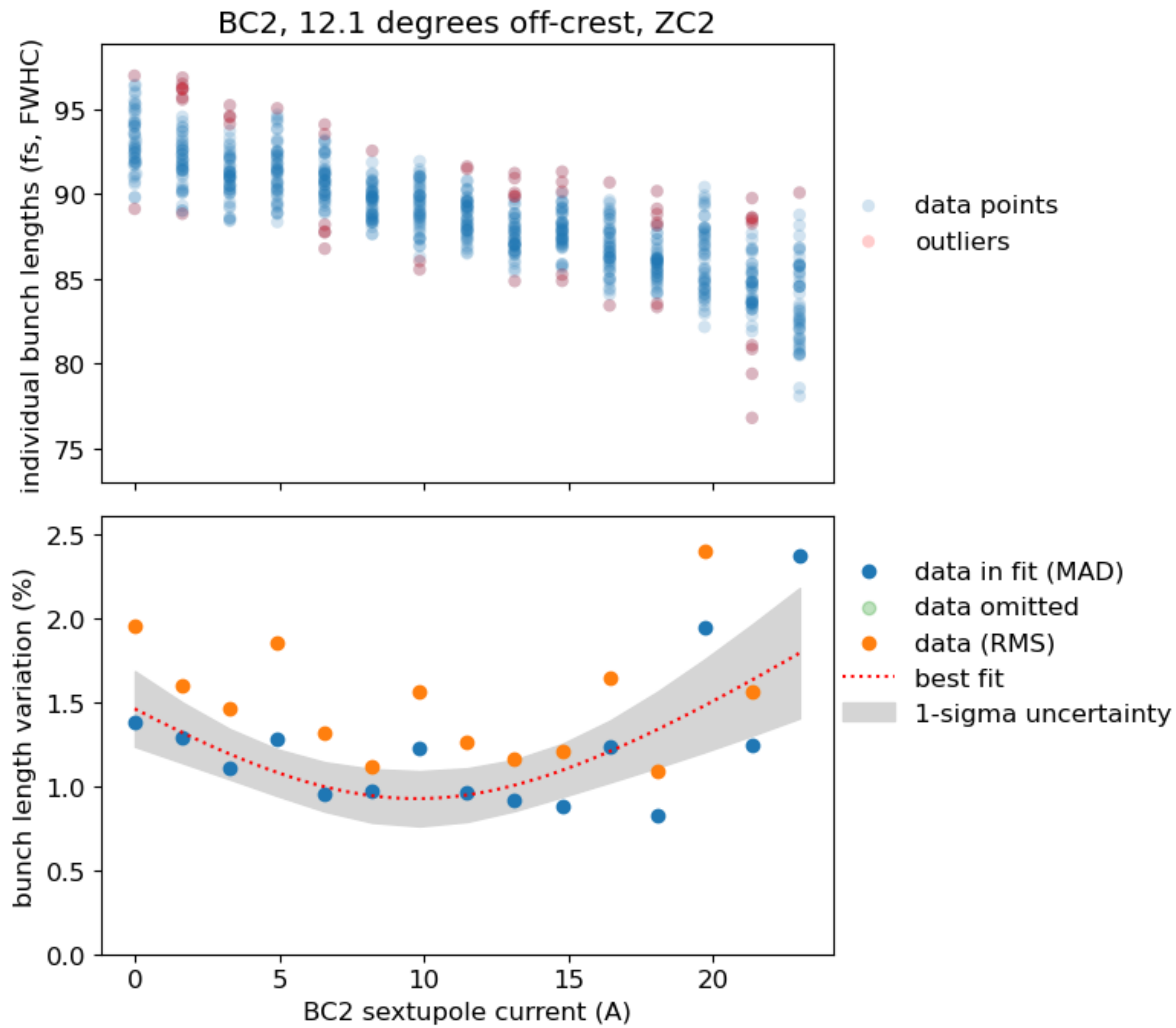


BUNCH COMPRESSION JITTER

Experimental results from MAX IV

> Compress in both compressors
  > Optimal sextupole setting for BC1
  > Scan BC2 sextupoles

> Much less clear of a trend than for BC1
  > Seen similar things in follow-up beamtimes
  > Possibly (likely?) additional effects
    > Both beam dynamics and diags
  > Working on it!



Bunch Compression Jitter

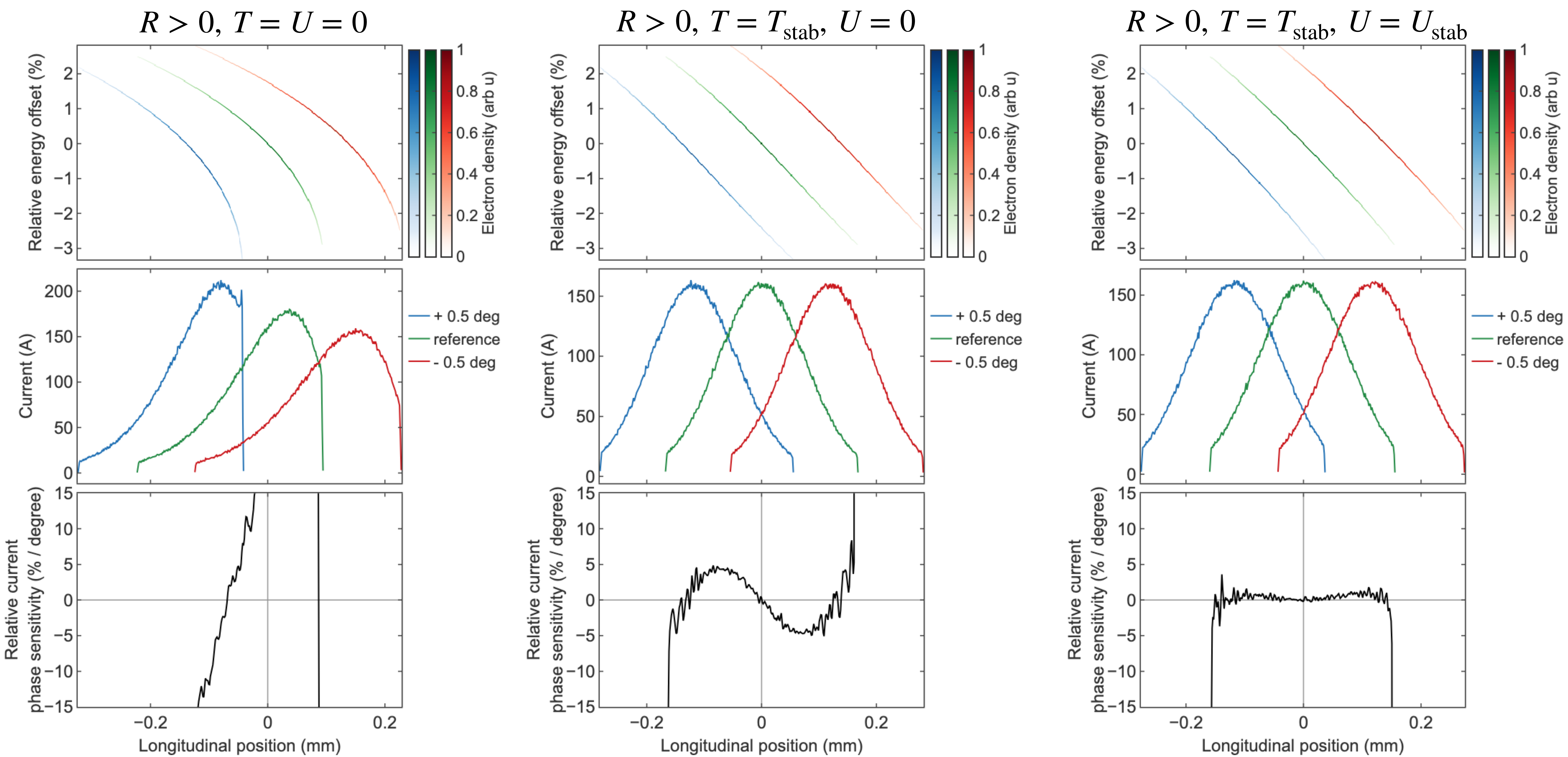
> A bit more rigorous…

$$\left.\frac{\partial_\phi C}{C_0}\right|_{z=0} = \frac{A}{\mathscr{E}_0}\left[C_0 R k\cos(\phi) - 2(C_0 - 1)\frac{T}{R}\sin(\phi)\right]$$

> Extends further: phase-jitter-induced linearization jitter eliminated when

$$U_{\text{stab}} = \frac{R}{2}\left(\frac{\mathscr{E}_0}{\Delta\mathscr{E}}\right)^2 \frac{1}{\tan^2(\phi)}\left(\frac{1}{\sin^2(\phi)} - \frac{2}{3}\right) = T_{\text{stab}}\frac{\mathscr{E}_0}{\Delta\mathscr{E}}\left(\frac{1}{\sin^2(\phi)} - \frac{2}{3}\right)$$

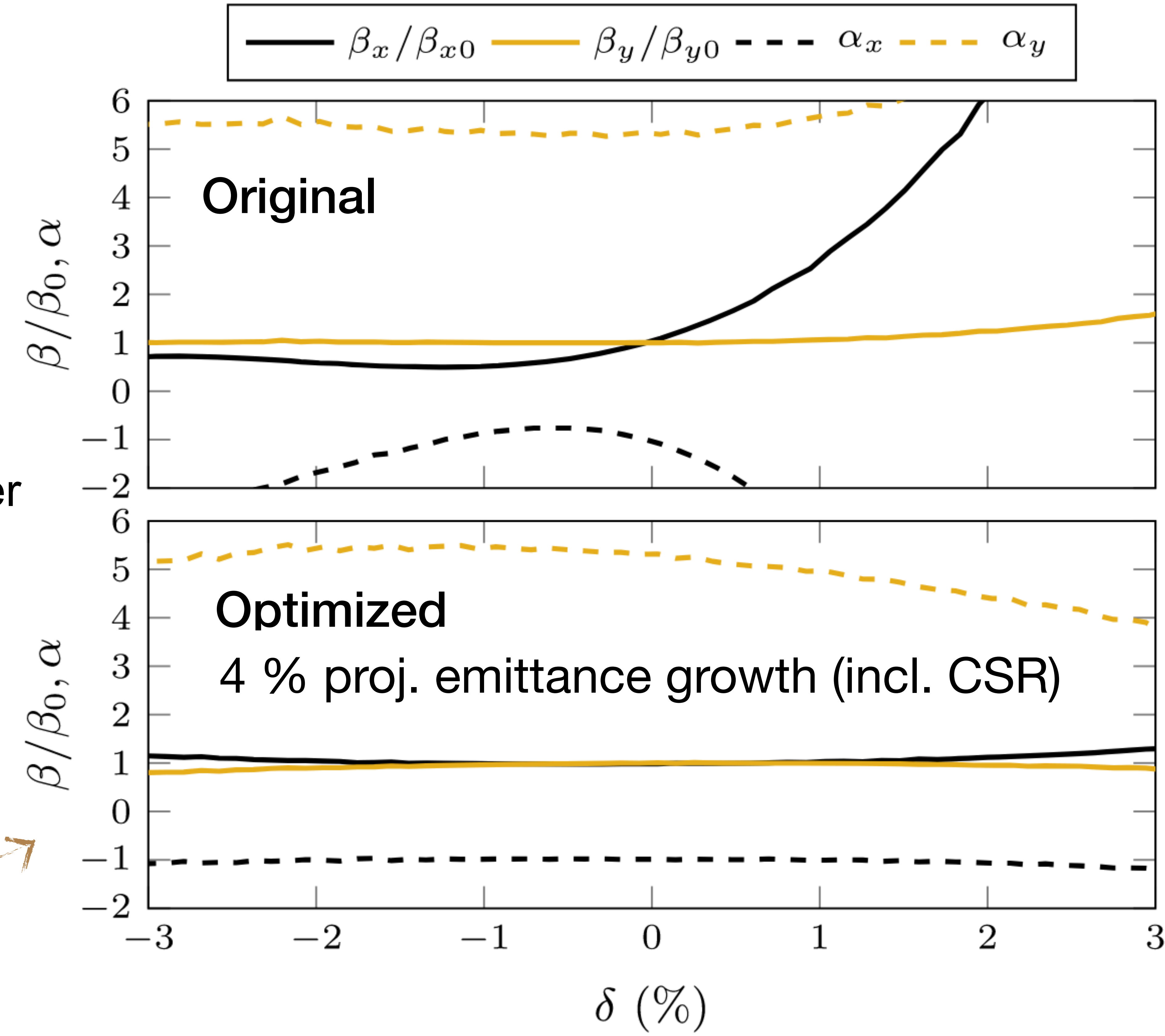
Bunch Compression Jitter



Practical Considerations

Practical Considerations

- **Cost**
  - The original intention was to save money
    - This is indeed the case
    - Simpler RF system - less HW, staff, infrastructure, …
    - Stability - magnet PSU on the PPM level, RF at least OoM larger
- **Collective effects**
  - "Complex" optics potentially offer control
    - CSR-mitigation
    - Optical microbunching mitigation
      - "Transverse Landau damping" [1]
  - Longitudinal wakes
    - Increase chirp - allow operation closer to crest
    - More energy-efficient acceleration



Björklund Svensson et al., Phys. Rev. Accel. Beams **22**, 104401 (2019)

See also e.g.
Björklund Svensson et al., NIM A **1033**, 166591 (2022)
P. H. Williams et al., Phys. Rev. Accel. Beams **23**, 100701 (2020)
Dixon et al., arXiv:2603.08318 (2026)

[1] A. D. Brynes et al., Phys. Rev. Accel. Beams **27**, 074402 (2024)

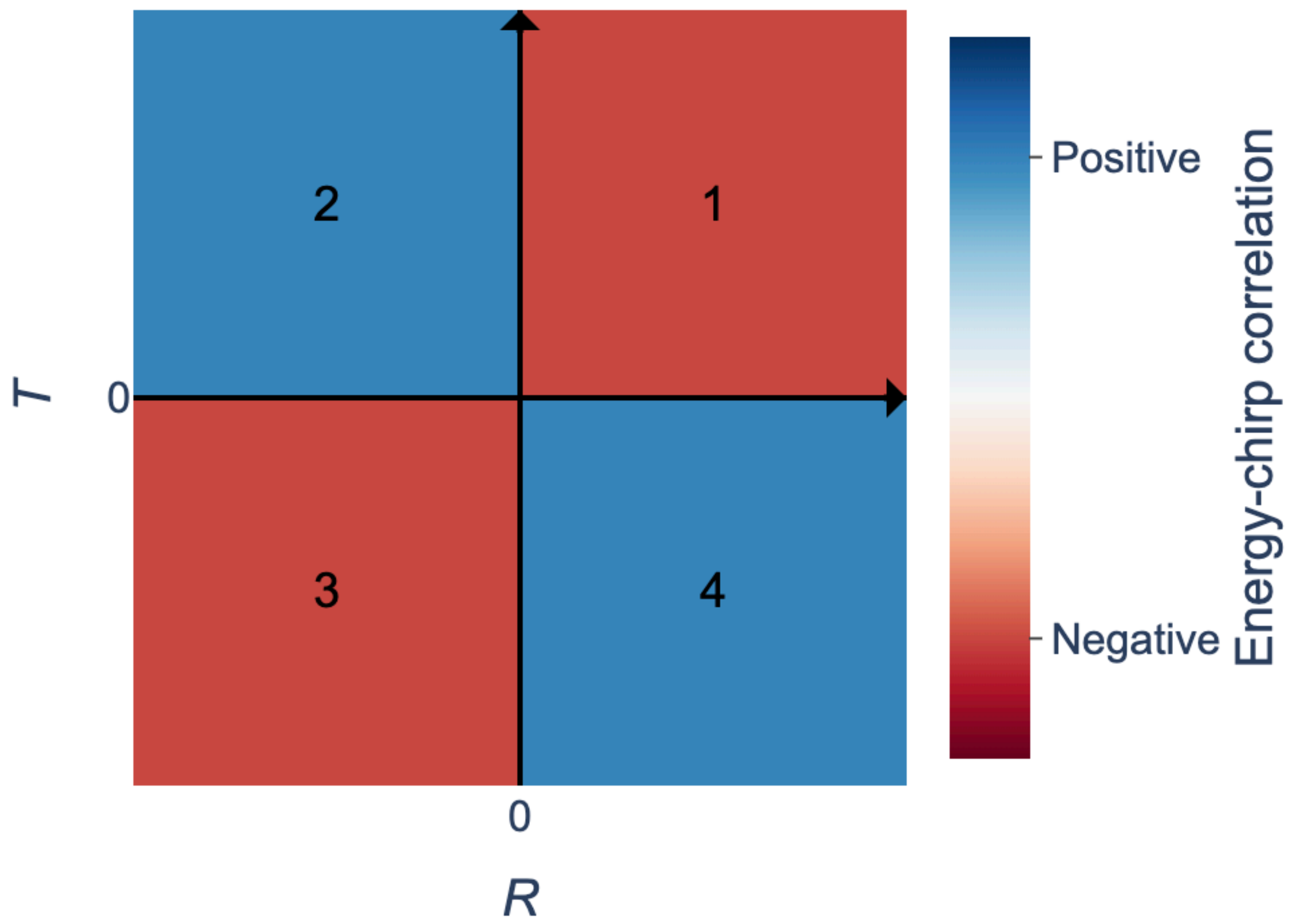
Conclusions and Outlook

Conclusions and Outlook

- Arc-like compressors are very useful for generating ramped current profiles
  - Nonlinear compression is stable and efficient
- Also offer compression-stabilizing effects
  - Work still ongoing, but physics relatively well-understood
  - Mechanism is general, does not only apply to RF accelerators
- Design seems compelling for PWFA applications
  - Current shaping straightforward
  - Can be co-optimized for compression stability
  - Can likely also mitigate collective effects

THANK YOU!

Bunch Compression Jitter



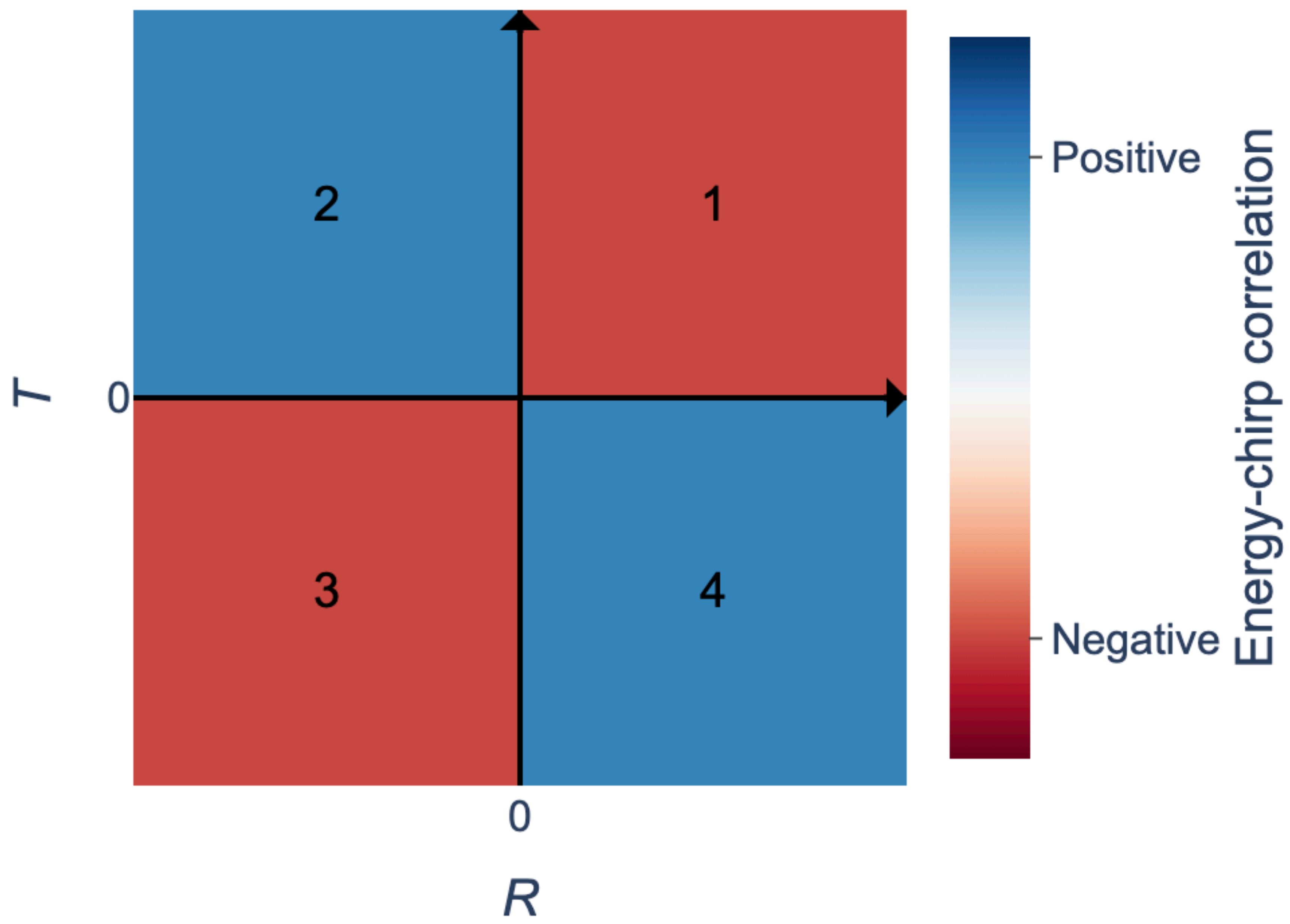
> Quite generally

$$\left.\frac{C'}{C_0}\right|_{z=0} = 2(C_0 - 1)\frac{T}{R}\delta' - C_0 R h' \quad \rightarrow \quad T_{\mathrm{stab}} = \frac{R^2}{2}\frac{C_0}{C_0 - 1}\frac{h'}{\delta'} = -\frac{R}{2}\frac{h'}{h}\frac{1}{\delta'}$$

> And differentiating again eventually gives

$$U_{\mathrm{stab}} = R\frac{hh'\delta'' + 2\delta'(h')^2 - hh''\delta'}{6h^2(\delta')^3} = \frac{R}{6}\left(\frac{h'}{h}\frac{\delta''}{(\delta')^3} + 2\left(\frac{h'}{h}\right)^2\frac{1}{(\delta')^2} - \frac{h''}{h}\frac{1}{(\delta')^2}\right)$$

Bunch Compression Jitter



- Valid for any type of accelerator+compressor
  - … but maybe hard to do analytically for e.g. plasmas
  - Qualitative analysis part of present work
  - More on the way

BUNCH COMPRESSION JITTER

- Could potentially handle some collective effects too
  - Longitudinal wakes reduce the energy of the bunch
    - Chirp is increased for positive off-crest phases (arc-like) - negative correlation
      - Same correlation sign as RF-stabilization
    - Chirp is decreased for negative off-crest phases (chicane-like) - positive correlation
      - Opposite sign to RF-stabilization