TeV Beams from Plasma Acceleration via Regenerative Cascading

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see arXiv:2607.07979 for more details

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Simulations done using OSIRIS and QPAD on Perlmutter@NERSC

Plasma accelerators for high-energy physics: the status and the challenge

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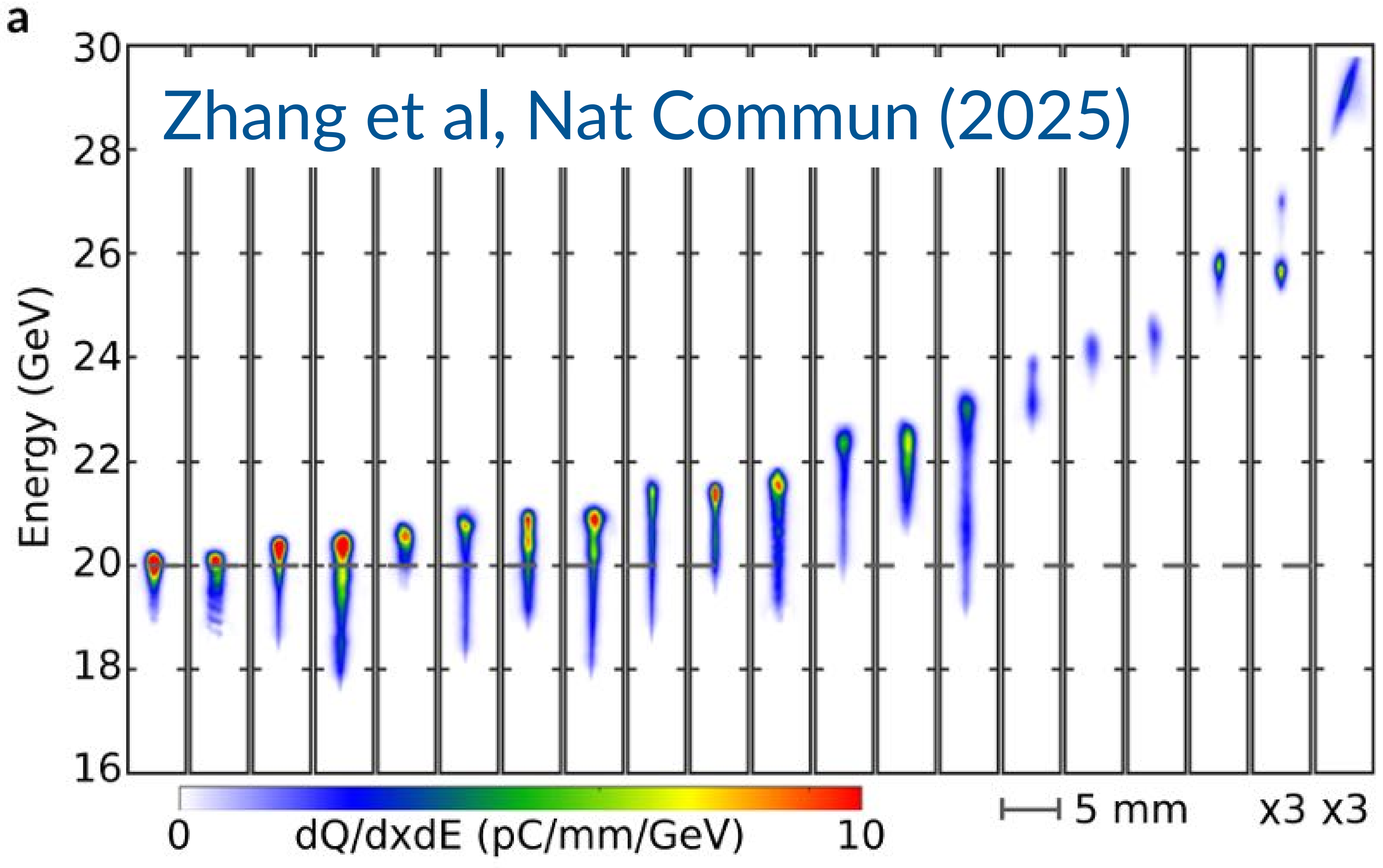
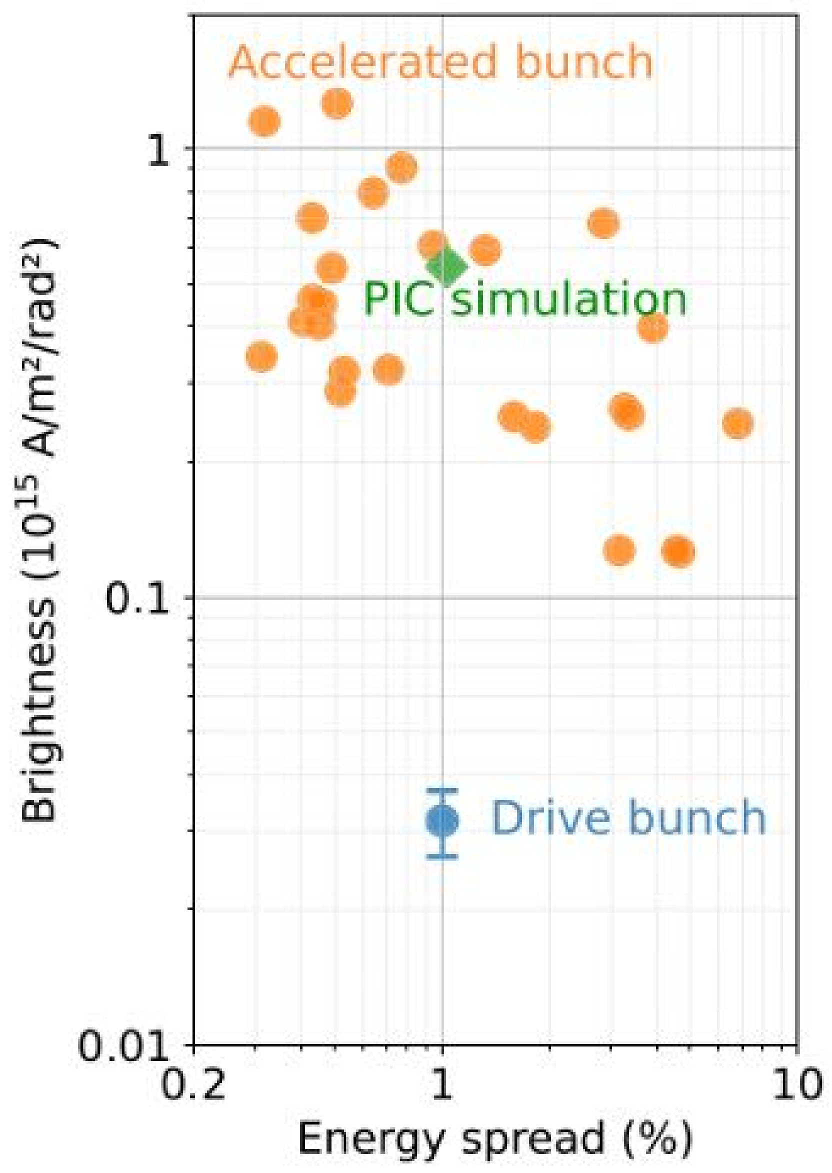
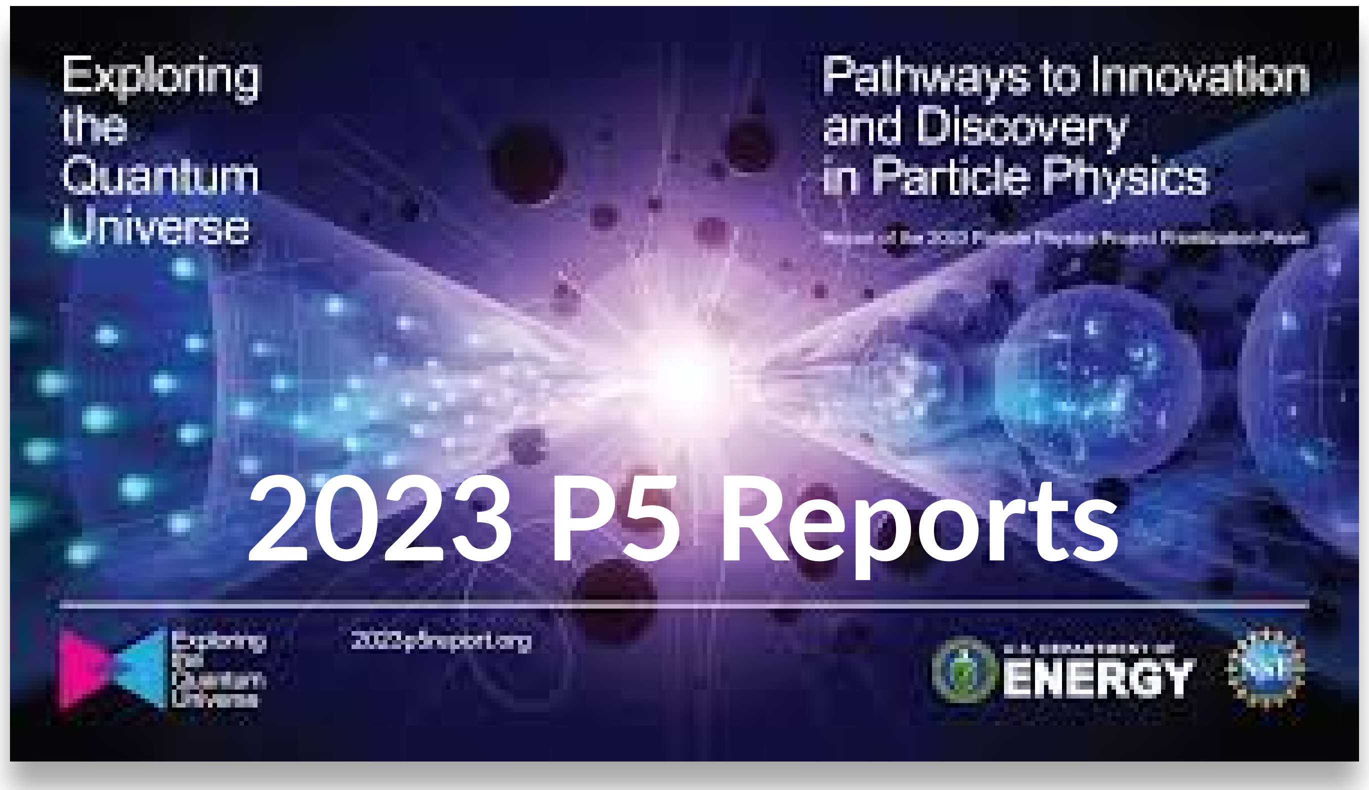
Plasma accelerators have produced multi-GeV, high-brightness electron beams with ~10 GeV/m gradient in a single stage

More examples:
Corde et al, Nat. Commun (2016)
Litos et al, PPCF(2016)
Litos et al, Nature (2014)
Picksley et al, PRL (2024)
Miao et al, PRX (2022)
Gonsalves et al, PRL (2019)
etc





Reaching TeV-scale energy remains a big challenge



The P5 (Particle Physics Project Prioritization Panel) released the decadal report in 2023, which recommends support for:

"4.a) R&D toward a cost-effective 10 TeV pCM **collider** based on proton, muon, or possible wakefield technologies."

How do you reach TeV-scale energy? Staging.

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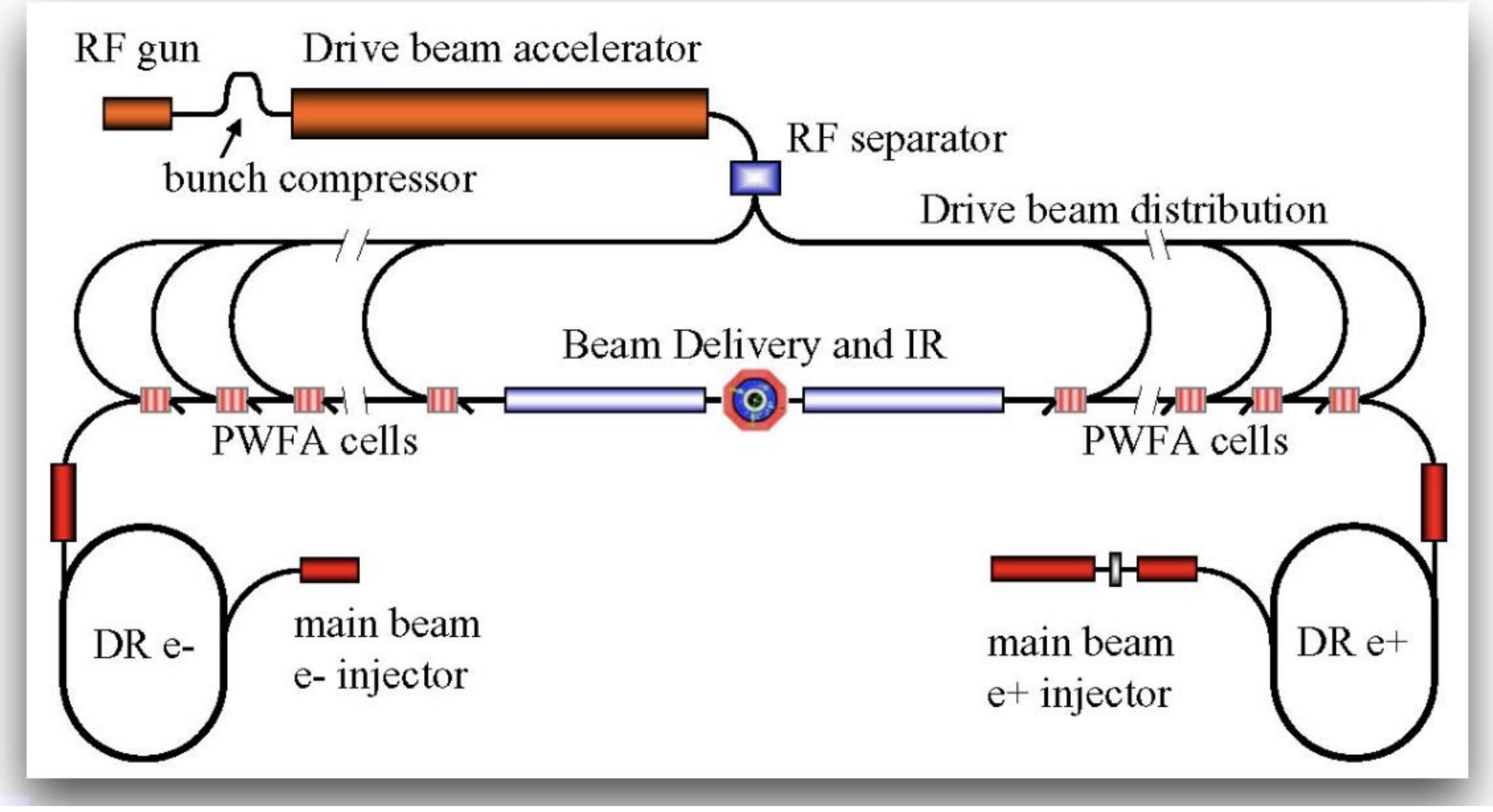
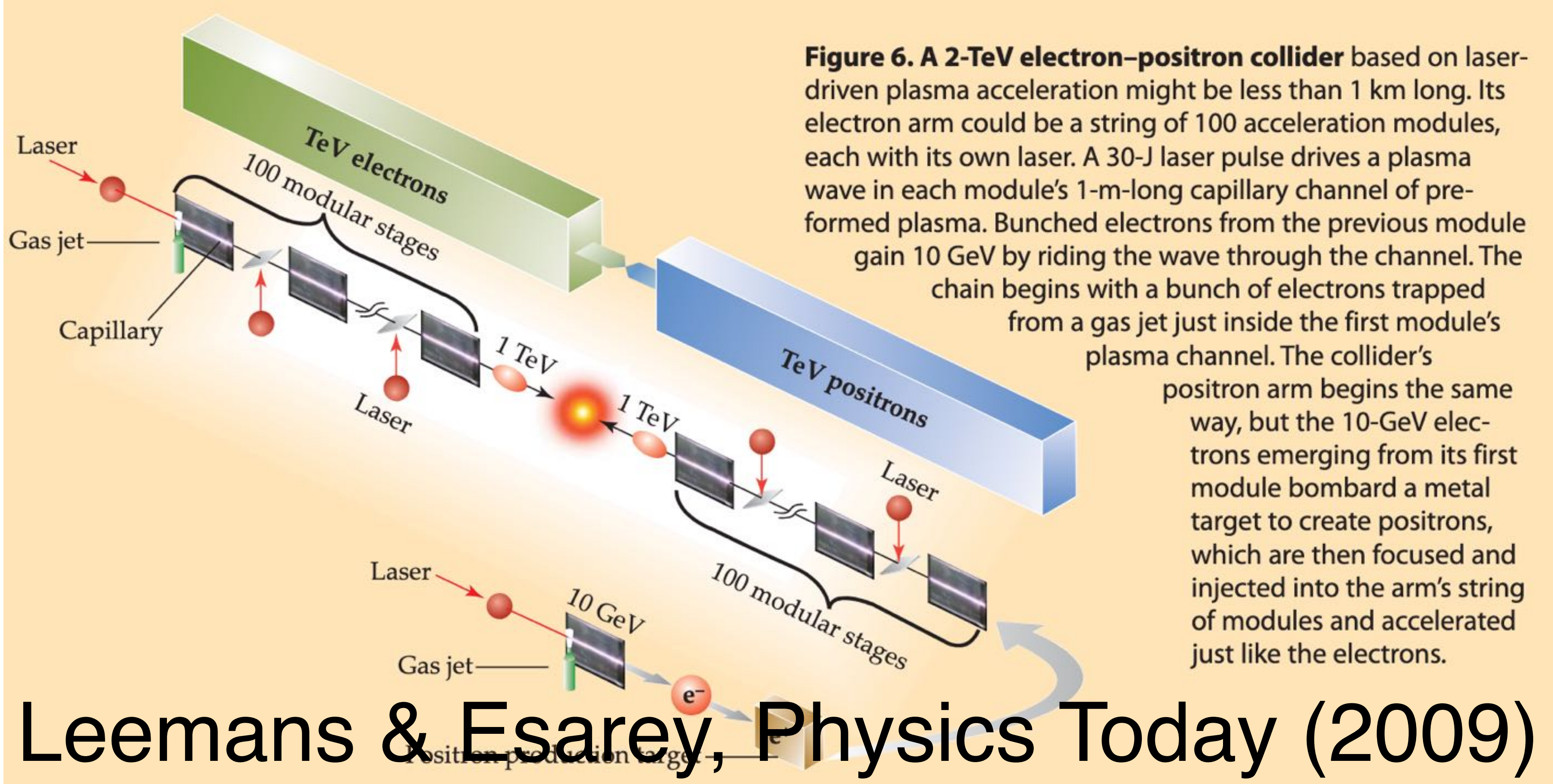
Using a laser or electron beam driver, ~10 GeV per stage demonstrated.
To reach TeV, we need to link 100 such stages

symmetric e-e+ collider design

SLAC-PUB-13766



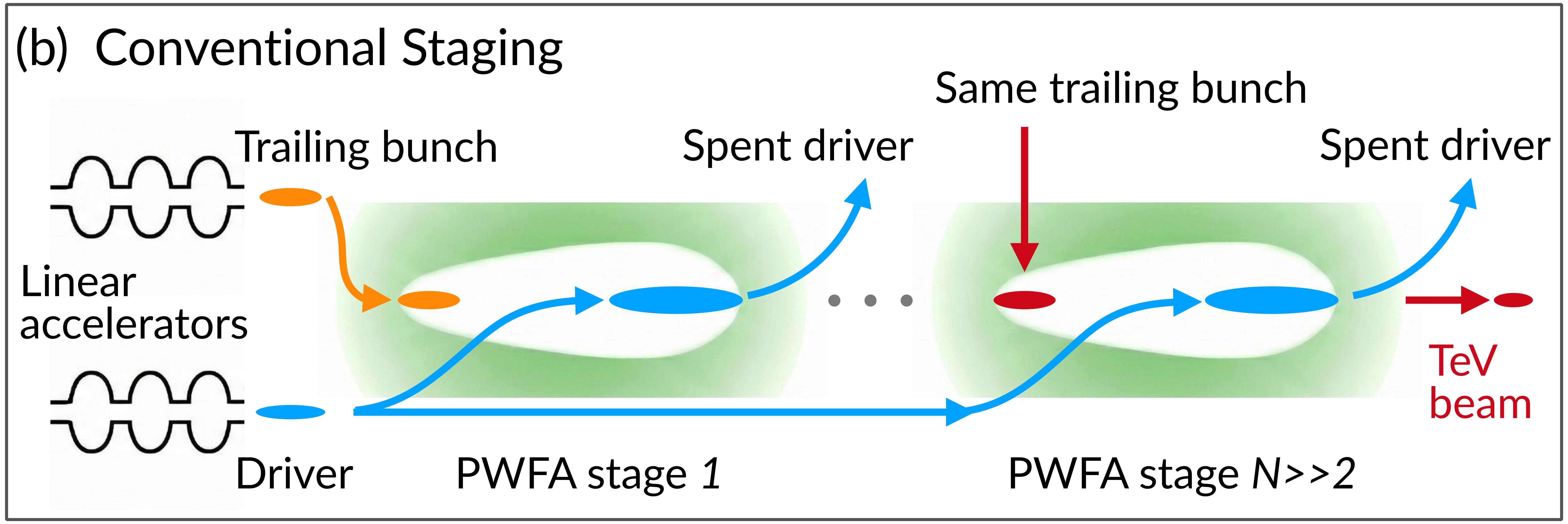


Leemans & Esarey, Physics Today (2009)

asymmetric e-e+ collider design

42 GeV e+ collides with 375 GeV e-; Separated linacs

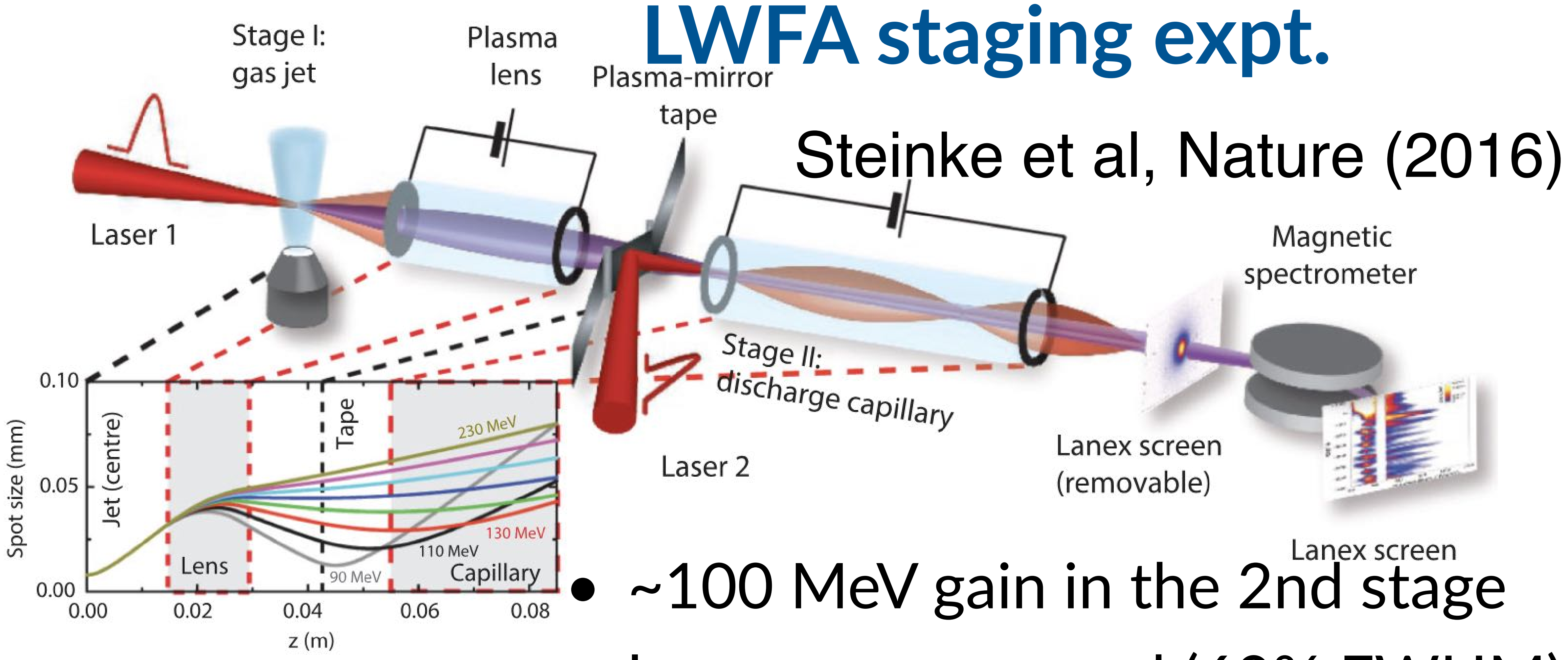
But staging is hard



- Same witness through all stages
- challenging alignment/sync/ matching
- energy scaling: linear addition
- brightness degrades
- many stages (lengthy/expensive optics)

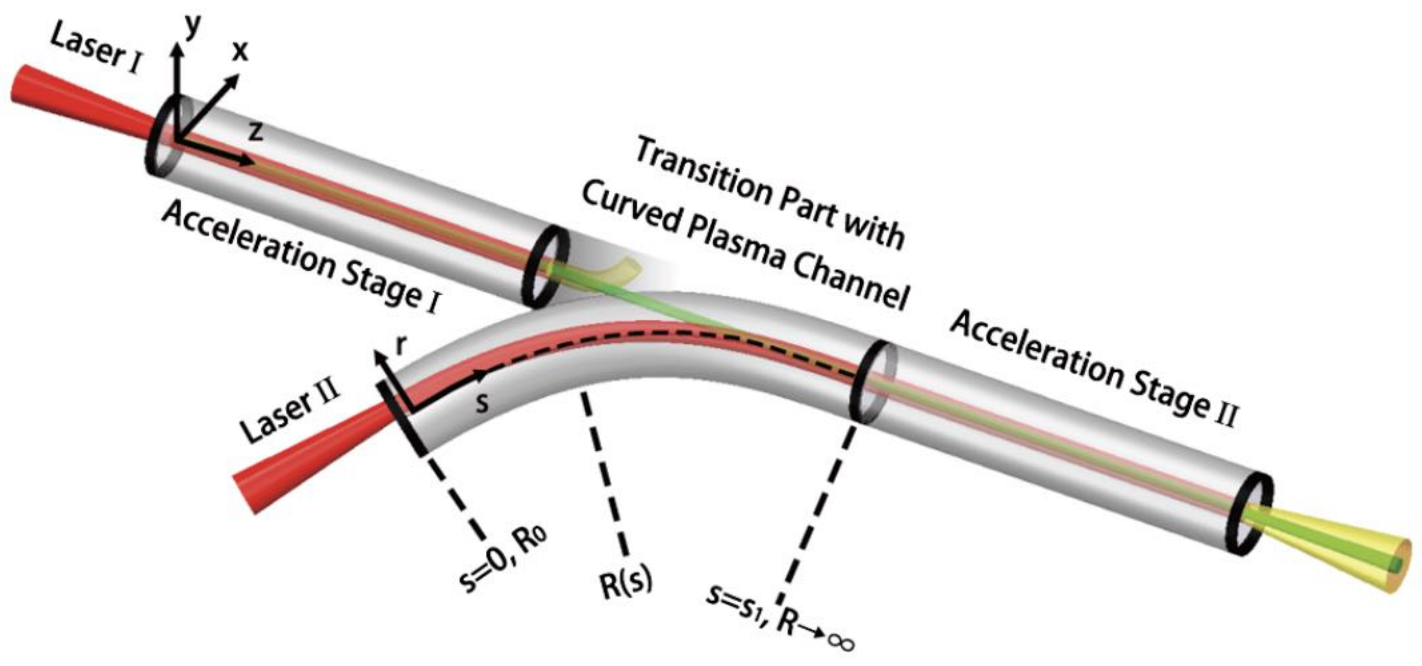
LWFA staging expt.

Steinke et al, Nature (2016)



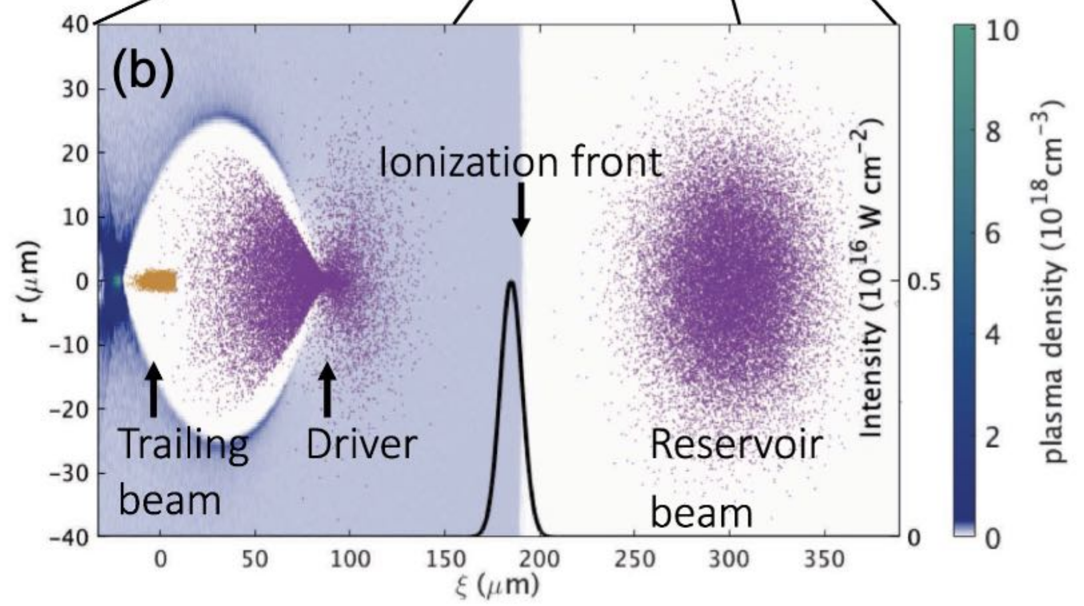
- ~100 MeV gain in the 2nd stage
- large energy spread (60% FWHM)
- low charge coupling efficiency (~3.5%)

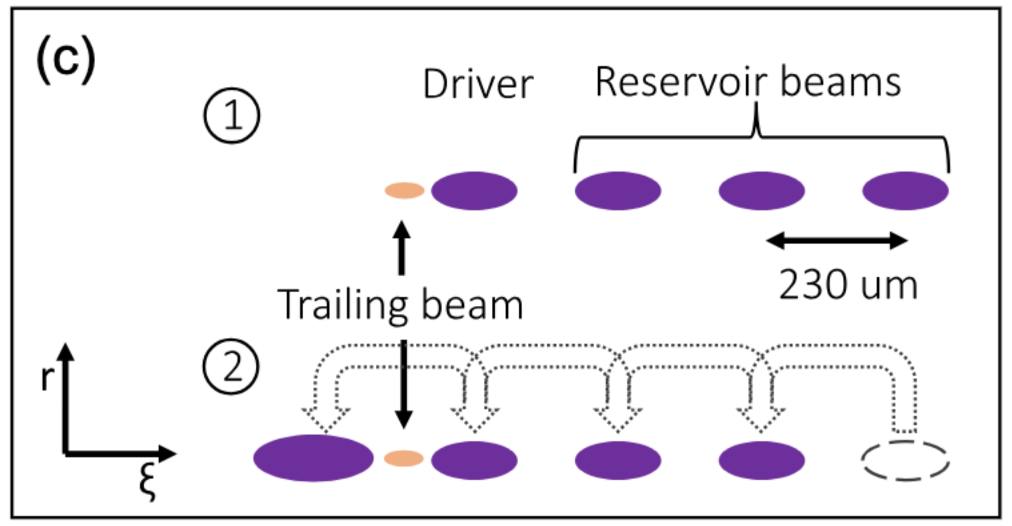
More staging ideas:



Luo et al, PRL (2018)

Knetsch et al, PRL (2023)





Or: get rid of the conventional staging

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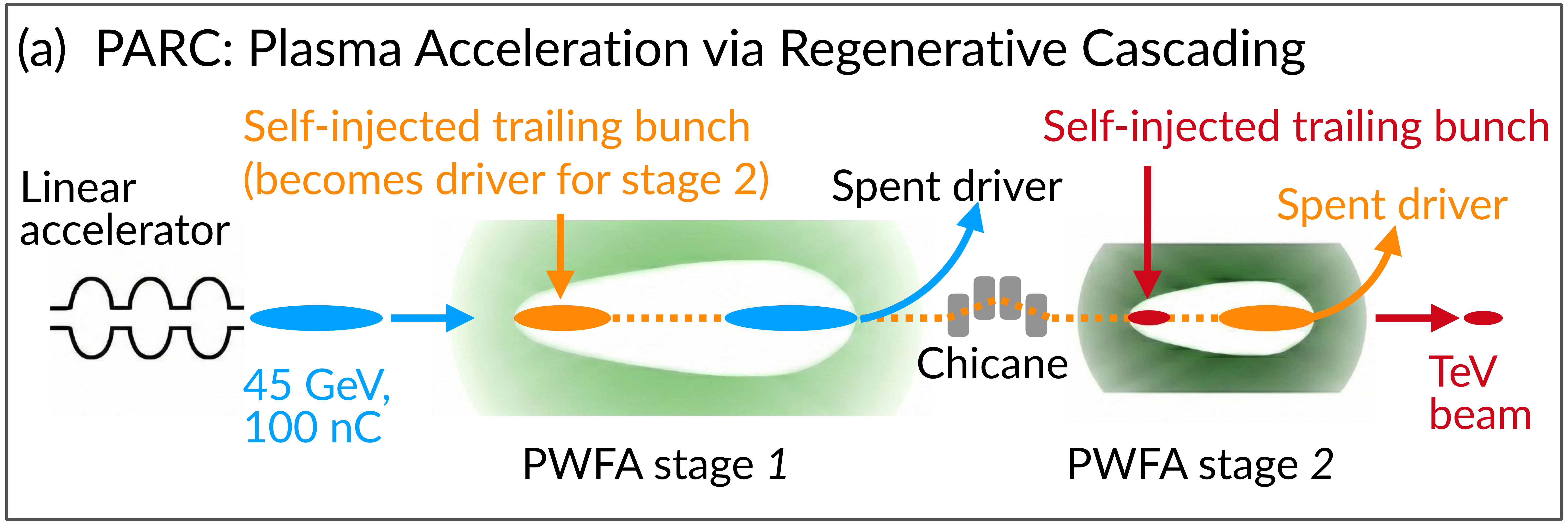
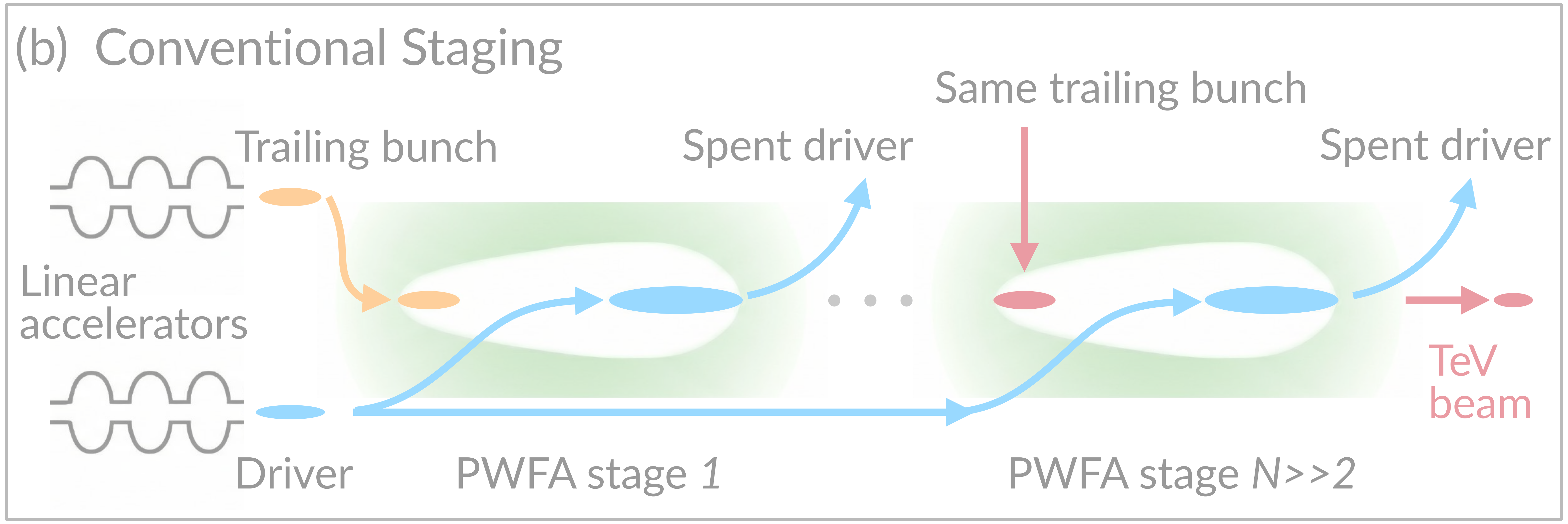


- Self-injected witness in each stage
- inherent alignment/sync/matching
- energy scaling: multiplication
- brightness boost (increasing plasma density)
- few stages (fewer optics)

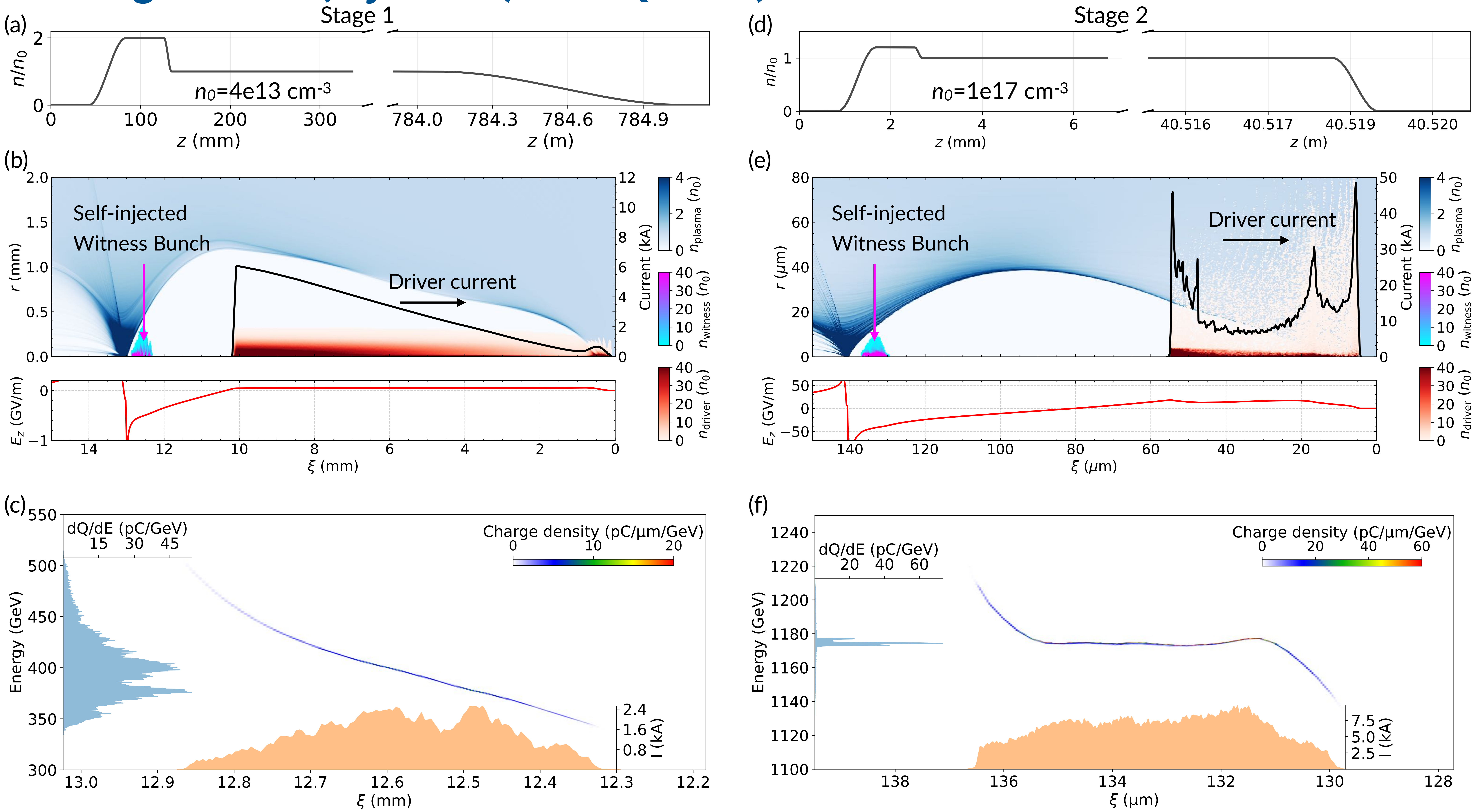


- Same witness through all stages
- challenging alignment/sync/matching
- energy scaling: linear addition
- brightness degrades
- many stages (lengthy/expensive optics)

Related concept: "self-similar staging using wake-induced ionization injection", Martinez de la Ossa et al., PoP (2015)

Start-to-end PIC simulation: 45 GeV in, 1.2 TeV out

- Starting with a 45 GeV, 100 nC drive bunch, we get a 1.2 TeV, 0.12 nC bunch in two stages
- Modeled using OSIRIS (injection) and QPAD (acceleration over 10s to 100s of meters)



Inter-stage compression modeled by beam-tracking (using Ocelot)

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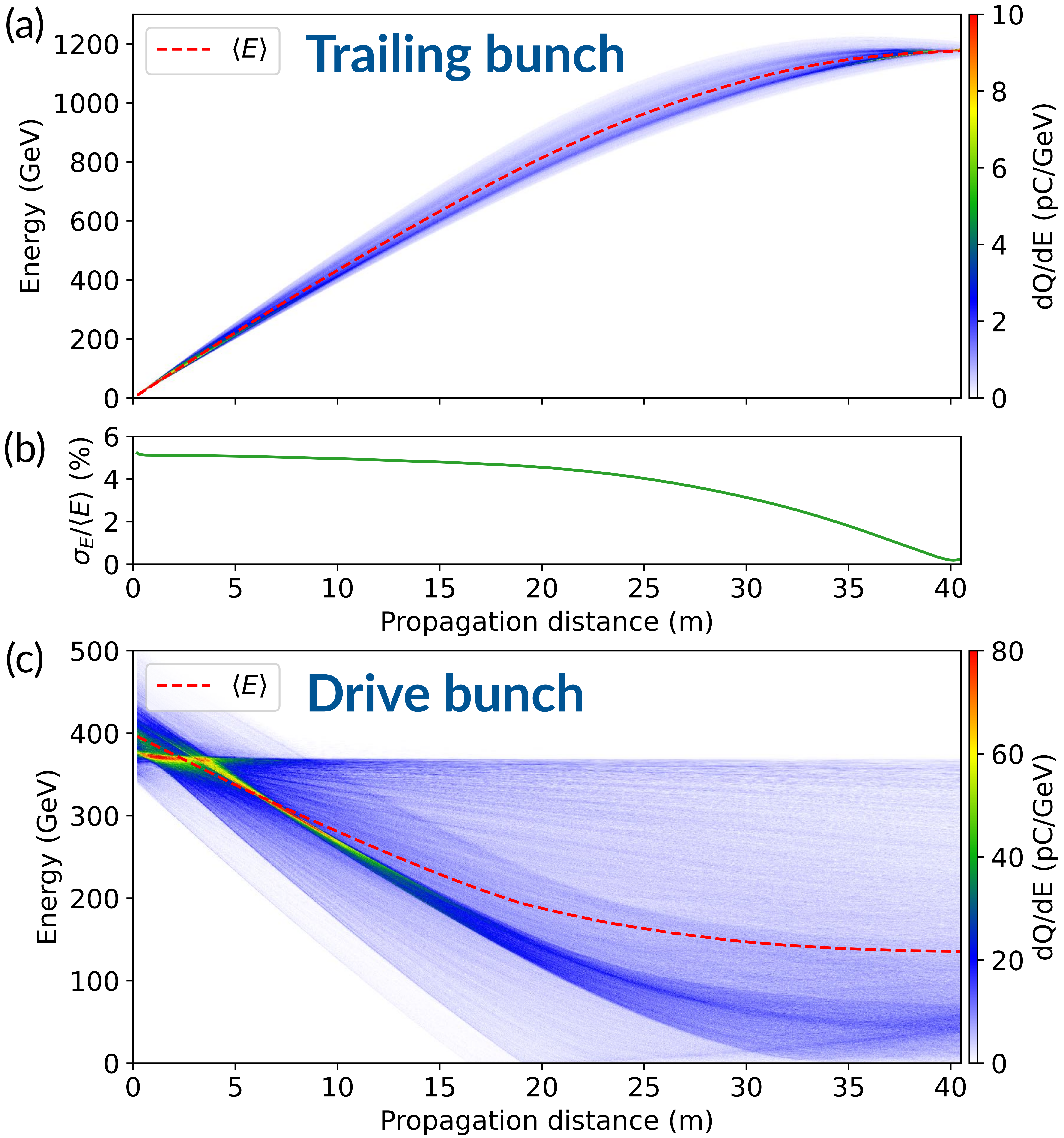
Large energy chirp —> "moderate" chicane (0.7 T, four-dipole, ~60 m)

Emittance growth negligible (<20%) — the 2nd stage does not care about it anyways

The evolving wake accelerates and dechirps at once

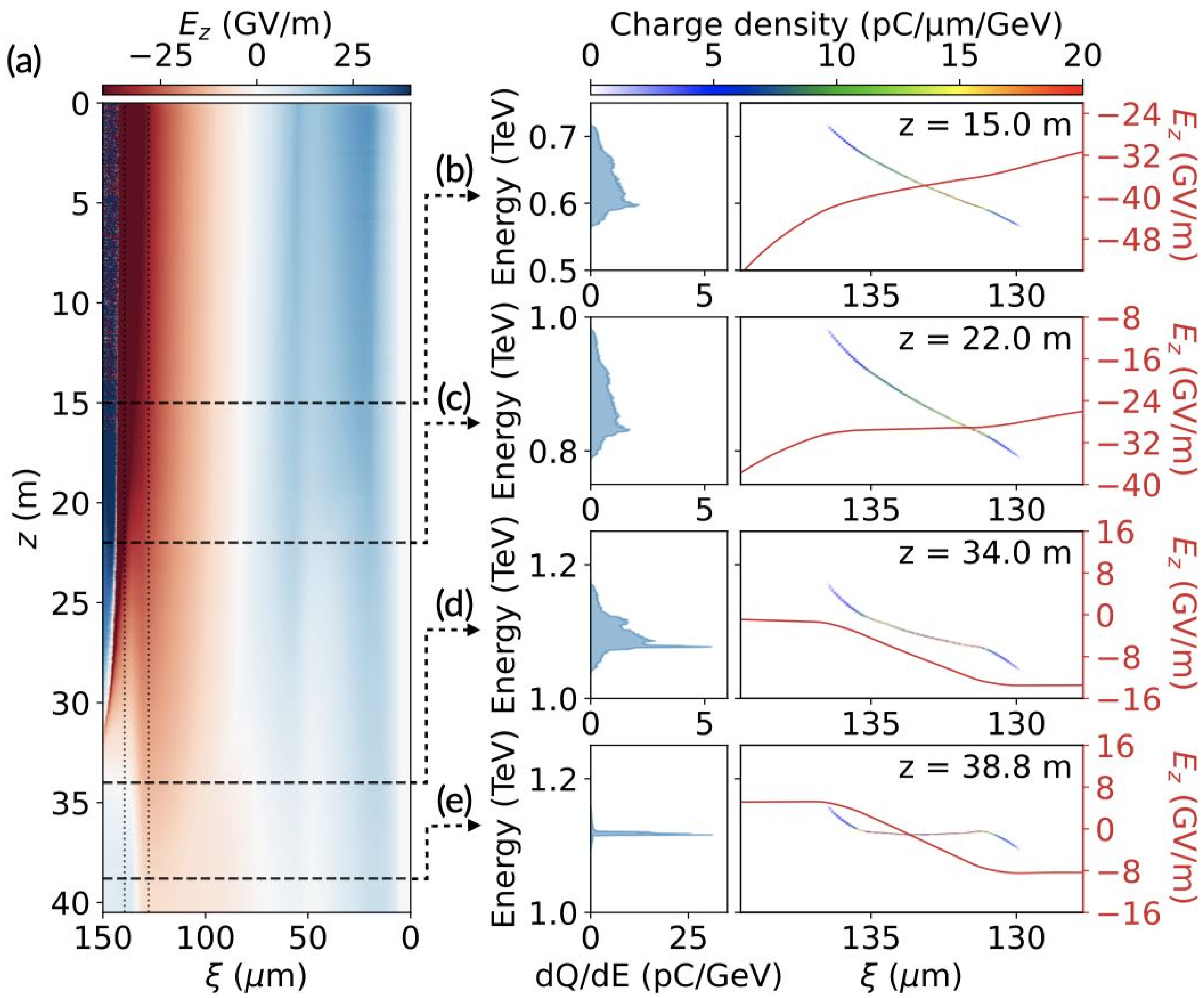


- Two phases:
  - 0-20 m, non-evolving wake — stable acceleration, constant ~5% energy spread (chirp)
  - beyond 20m, driver partially depletes — constantly evolving wake acts as a built-in dechirper

- Field transformer ratio ~2
- Energy transformer ratio ~3 (additional energy gained beyond pump partial depletion)

- Dynamic beam loading reduces the energy spread from 5% to ~0.3% (projected)
- Slice energy spread 0.02%

Dynamic beam loading delivers 0.2% projected spread



- 1.18 TeV, 0.12 nC
- efficiency: ~3% (5x room for improvement)
- peak current 8 kA
- normalized emittance 4 mm-mrad

- Total plasma length 825 meters
- Two stages (one inter-stage optics)

- 1st stage 785 m is a working point, not fully optimized (could be halved)

Similar DBL effects also observed in T. N. Dalichaouch et al, PRR (2025)

PARC vs conventional staging

- **In PARC, self-injected trailing bunch is automatically aligned, synchronized, and matched to the wake**
- **Different energy and efficiency scaling**

PARC:

$$E_N = E_0 \prod_{i=1}^{N} R_i$$

$$Q_N = Q_0 \prod_{i=1}^{N} (\eta_i R_i^{-1}) \propto \bar{\eta}^N$$

Conventional staging:

$$E_N = E_0 \sum_{i=1}^{N} R_i$$

$$Q_N = Q_0 / N \sum_{i=1}^{N} (\eta_i R_i^{-1}) \propto \bar{\eta}$$

Energy multiplies, goes up more rapidly, at the cost of lower efficiency)
—> favors large R and small N

- **The trailing bunch brightness resets in every stage**
  - the injection in the last stage matters the most
  - no need for a high-quality driver (plasma acts as an energy/brightness dual transformer)

A near-term test: EIC's spare/spent beam as a driver

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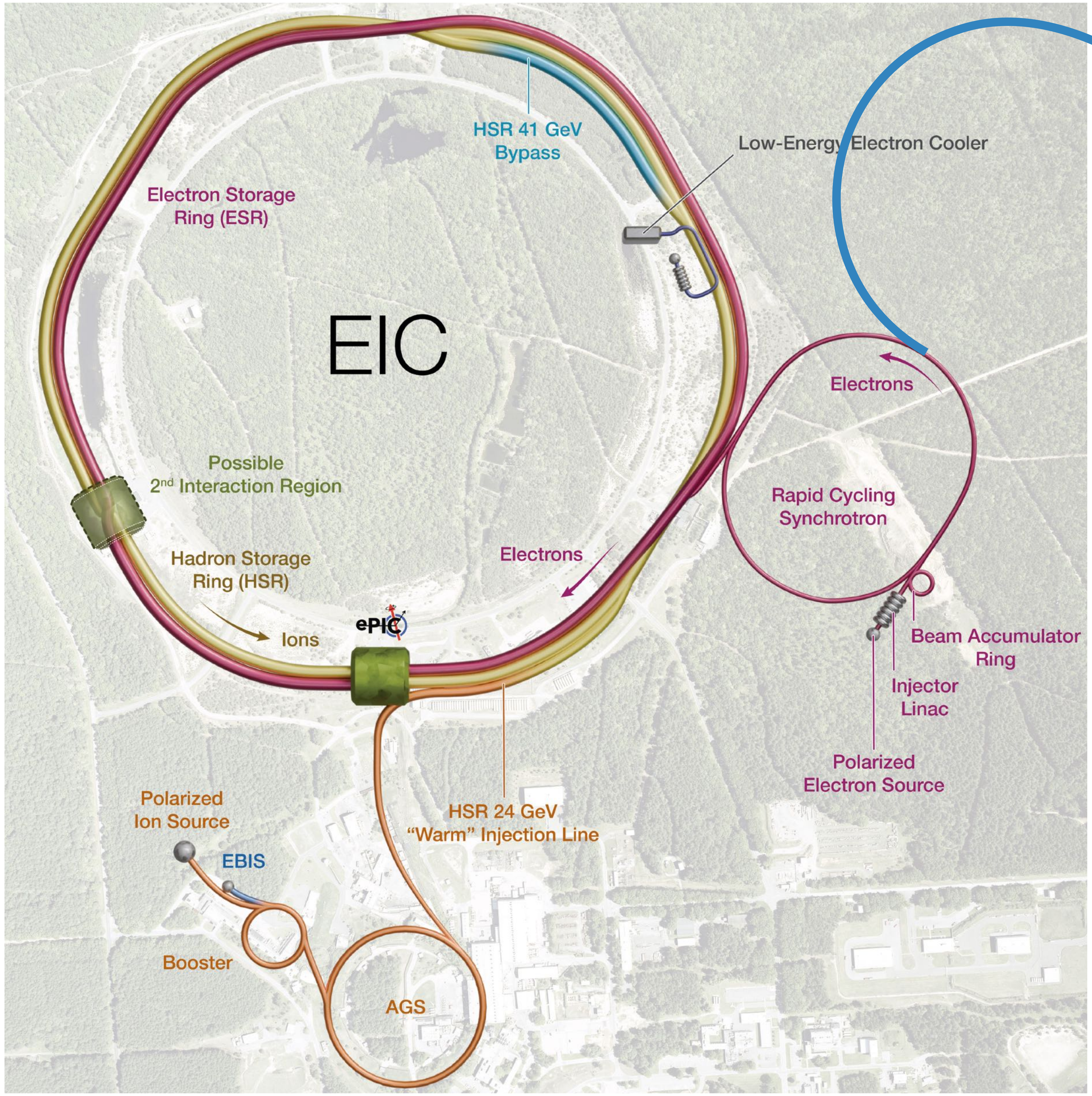
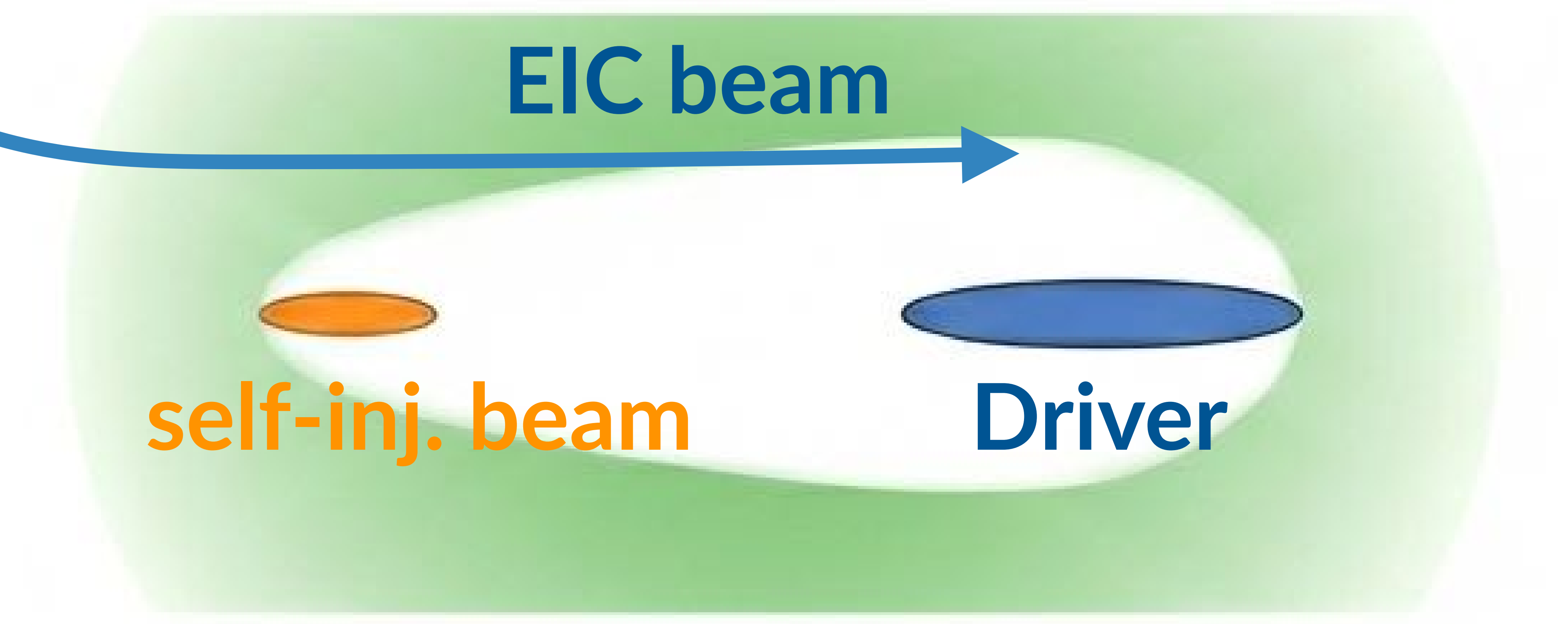
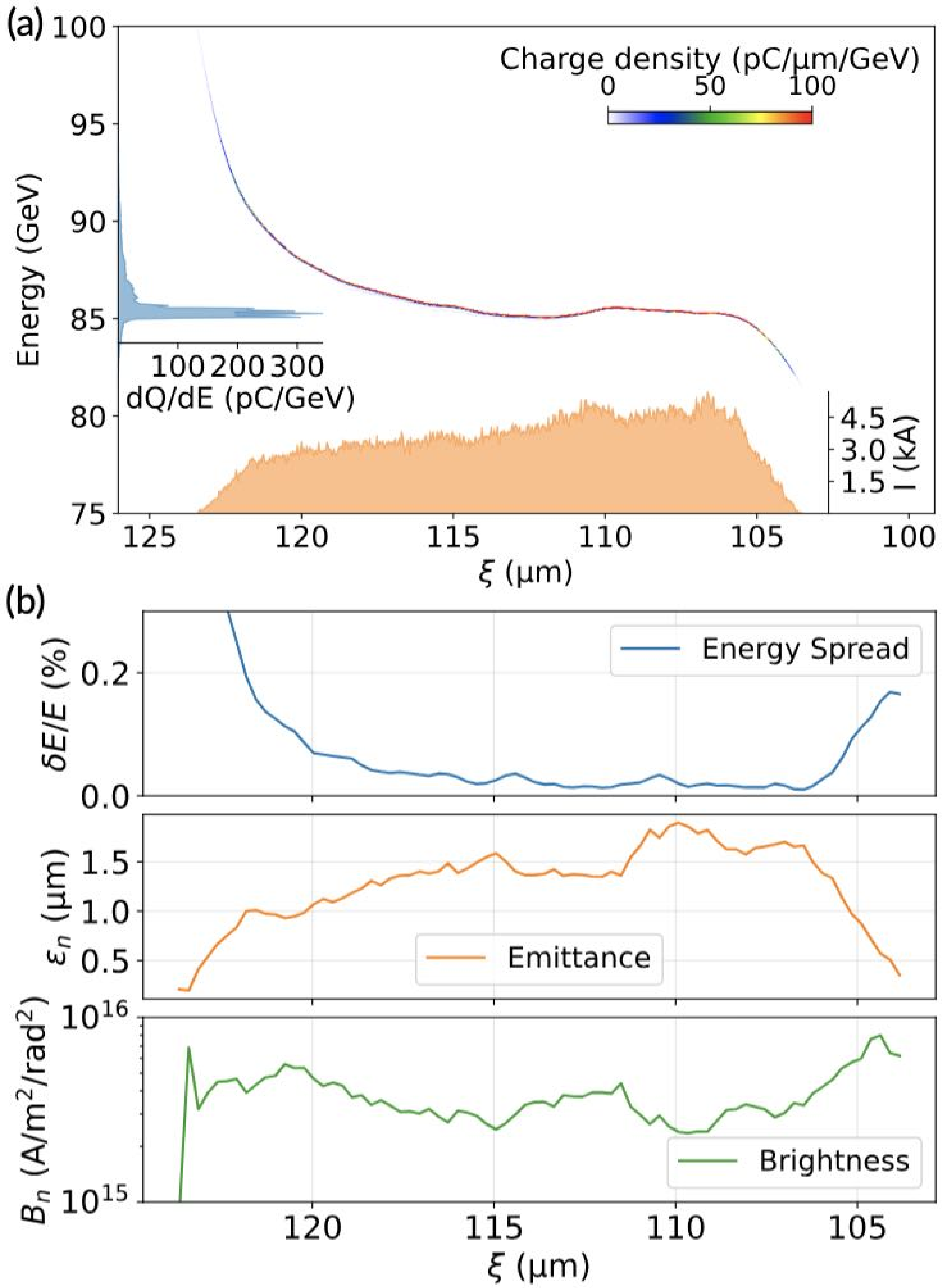




- 10 GeV beam energy
- 28 nC bunch charge
- 23 ps bunch length (compressible to kA)
- 400 mm·mrad normalized emittance
- Dumped frequently (to maintain polarization)
- Currently discarded — could drive PWFA

86 GeV in two stages



- Driver:
  - 10 GeV, 28 nC, 400 mm·mrad emittance
- Plasma:
  - Stage 1: 55 meters @ 5e14 cc
  - Stage 2: 4 meters @ 1e17 cc
- Final injected bunch:
  - 86 GeV in two stages
  - 0.2 nC
  - rms energy spread:
    0.8% projected and 0.02% slice
  - peak current 5 kA
  - normalized emittance 1.4 mm·mrad

Summary

- Reaching TeV energies using PWFA requires tens to hundreds of stages
- Staging is an unsolved problem — not limited by physics but by stringent alignment, synchronization, and matching challenges
- We propose the “Plasma Acceleration via Regenerative Cascading” idea to bypass the conventional staging challenges
  - A fresh bunch is injected in each stage and accelerated, then becomes the driver for the next stage
  - TeV in two stages, sub-percent spread, µm-level emittance, in less than 1 km plasma
  - A near-term test could be conducted using the EIC beam