UNIVERSITY OF OSLO

HALHF:

A Hybrid, Asymmetric, Linear Higgs Factory

Combining the strengths of RF and plasma-based accelerators

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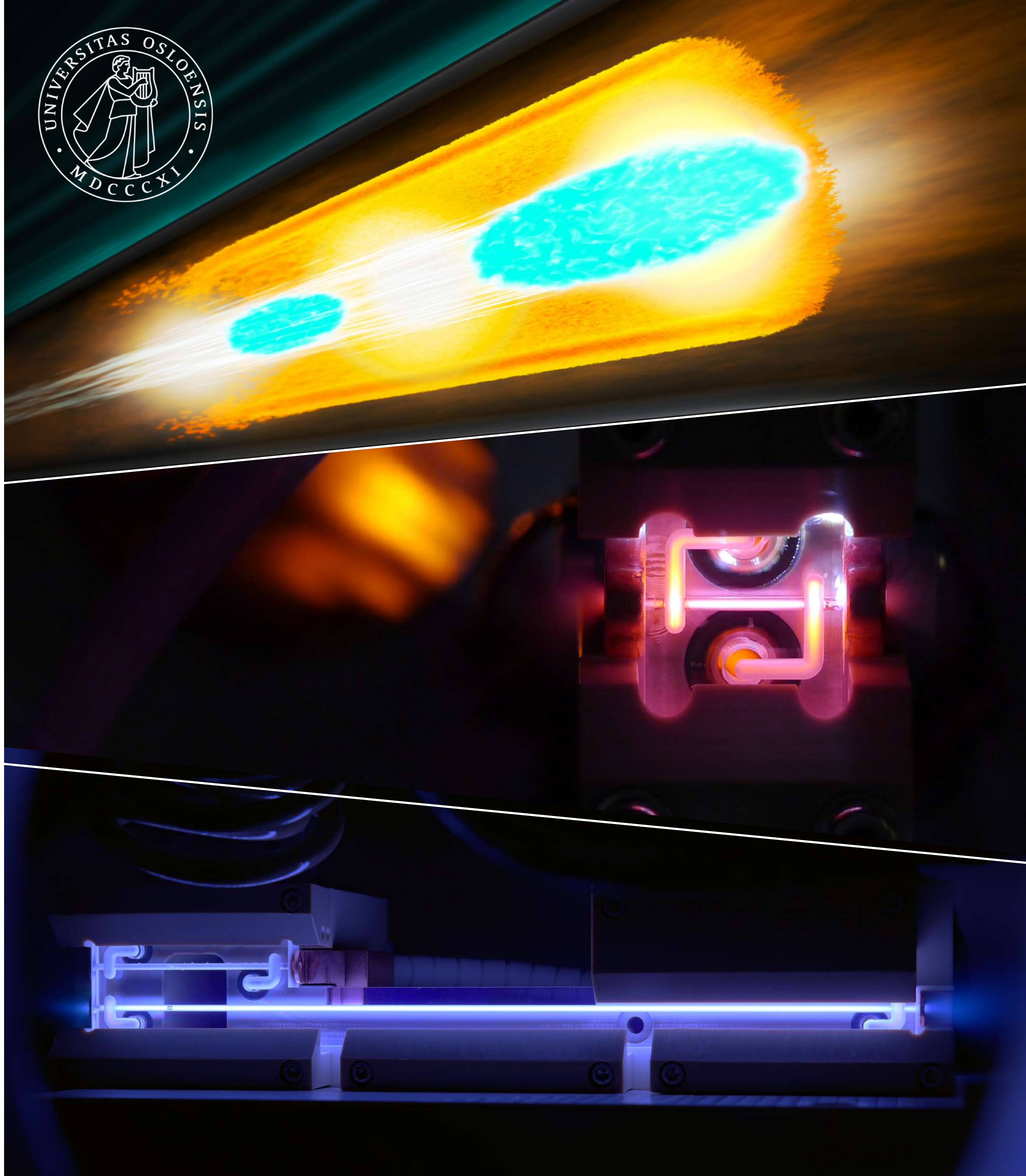
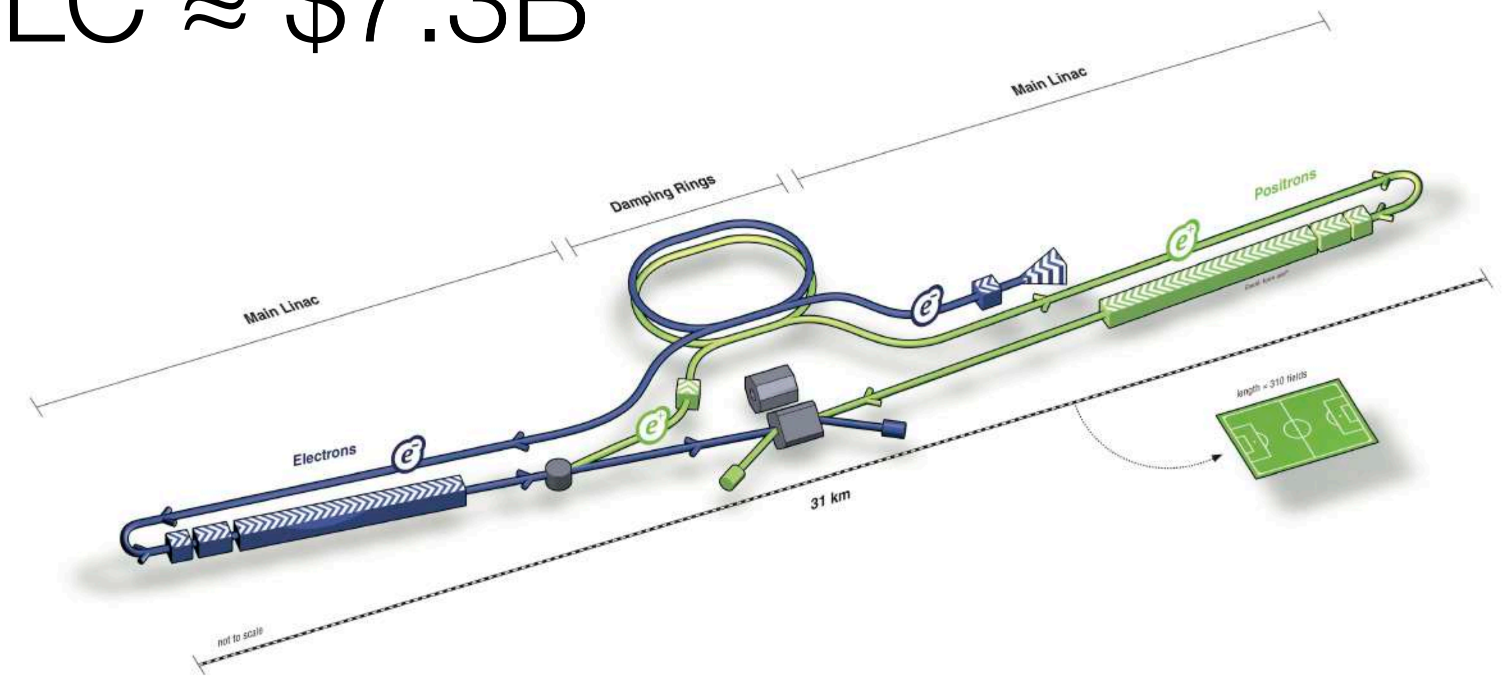
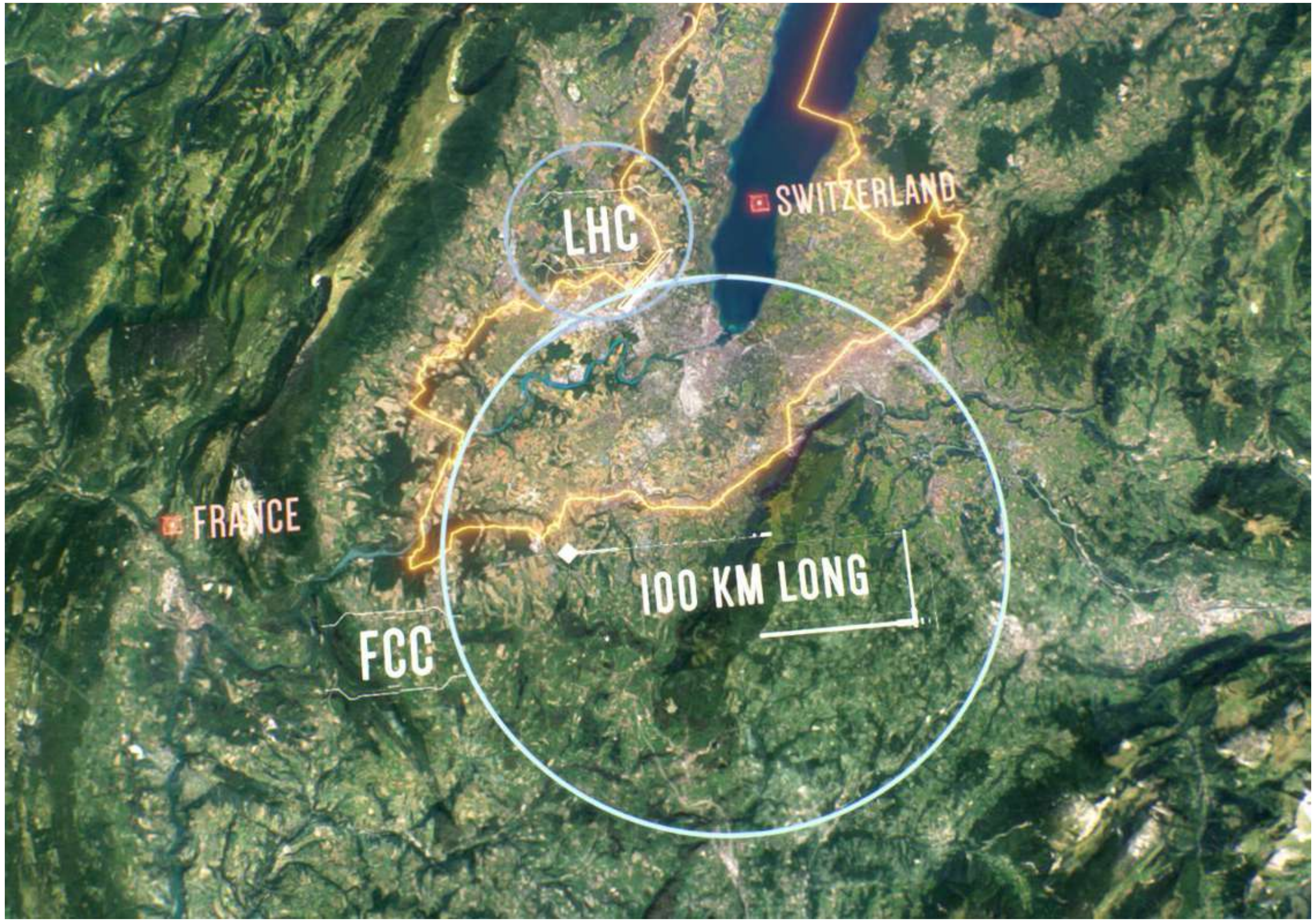


Motivation: **High energy physics risks becoming too expensive**

- Post-LHC era approaches (~2040)
- Next: Electron–positron collider
  - Precision studies of the Standard Model (Higgs, etc.)
- Estimated cost (Snowmass ITF):
  - FCC-ee ≈ $14.6B
  - ILC ≈ $7.3B



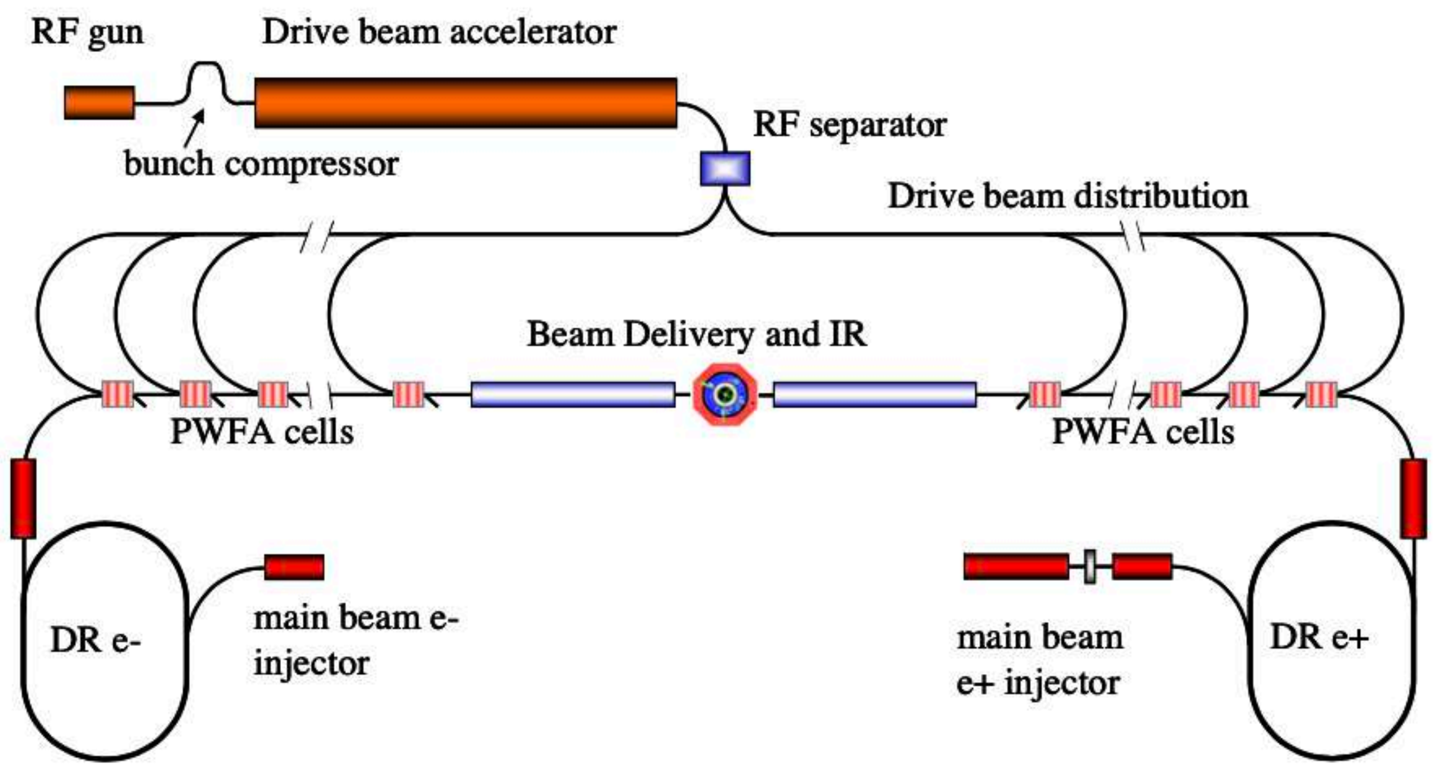
International Linear Collider. *Source: ILC*



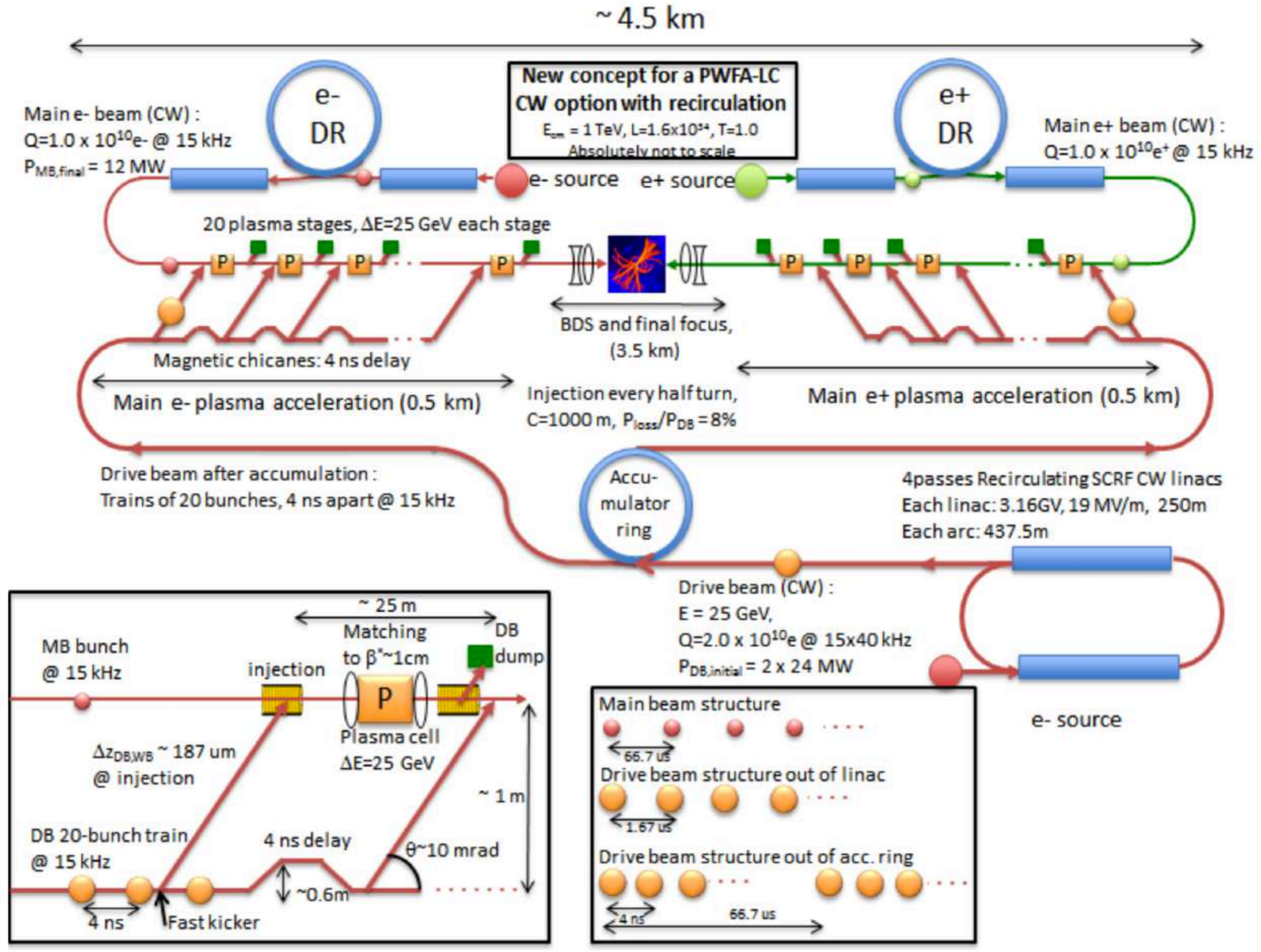
Future Circular Collider. *Source: CERN*

Solution: **A plasma-based e⁺e⁻ collider?**

- Footprint of RF colliders dominated by main linacs:
  - Use plasma-based accelerators (GV/m)
- Several proposals over the past decades:
  - Rosenzweig *et al.* (1996)
  - Pei *et al.* (2009)
  - Schroeder *et al.* (2010)
  - Adli *et al.* (2013)
- **Simplistic, but useful exercises to focus the R&D**
- Some key challenges have been identified:
  - Positron acceleration
  - Energy efficiency



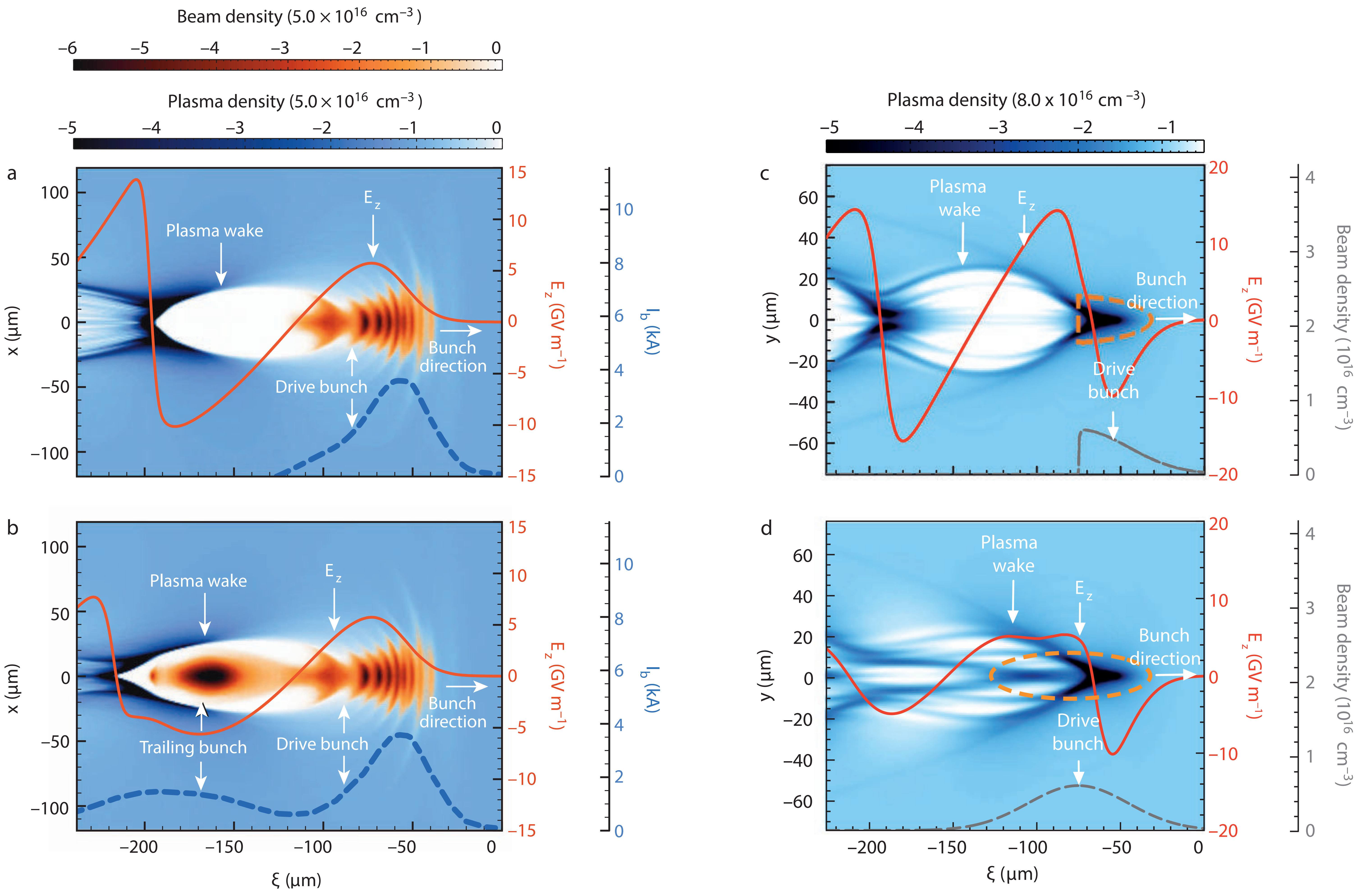
Source: Pei et al., Proc. PAC (2009)



Source: Adli et al., Proc. Snowmass (2013)

Main problem: **Positron acceleration in plasmas**

- Plasmas = charge asymmetric
  - No “blowout regime” for e^+
- Positron acceleration has been demonstrated.
  - Several schemes proposed to improve beam quality.
    — but lack of e^+ test facilities



Source: Litos et al. Nature 515, 92 (2014), Corde et al. Nature 524, 442 (2015).

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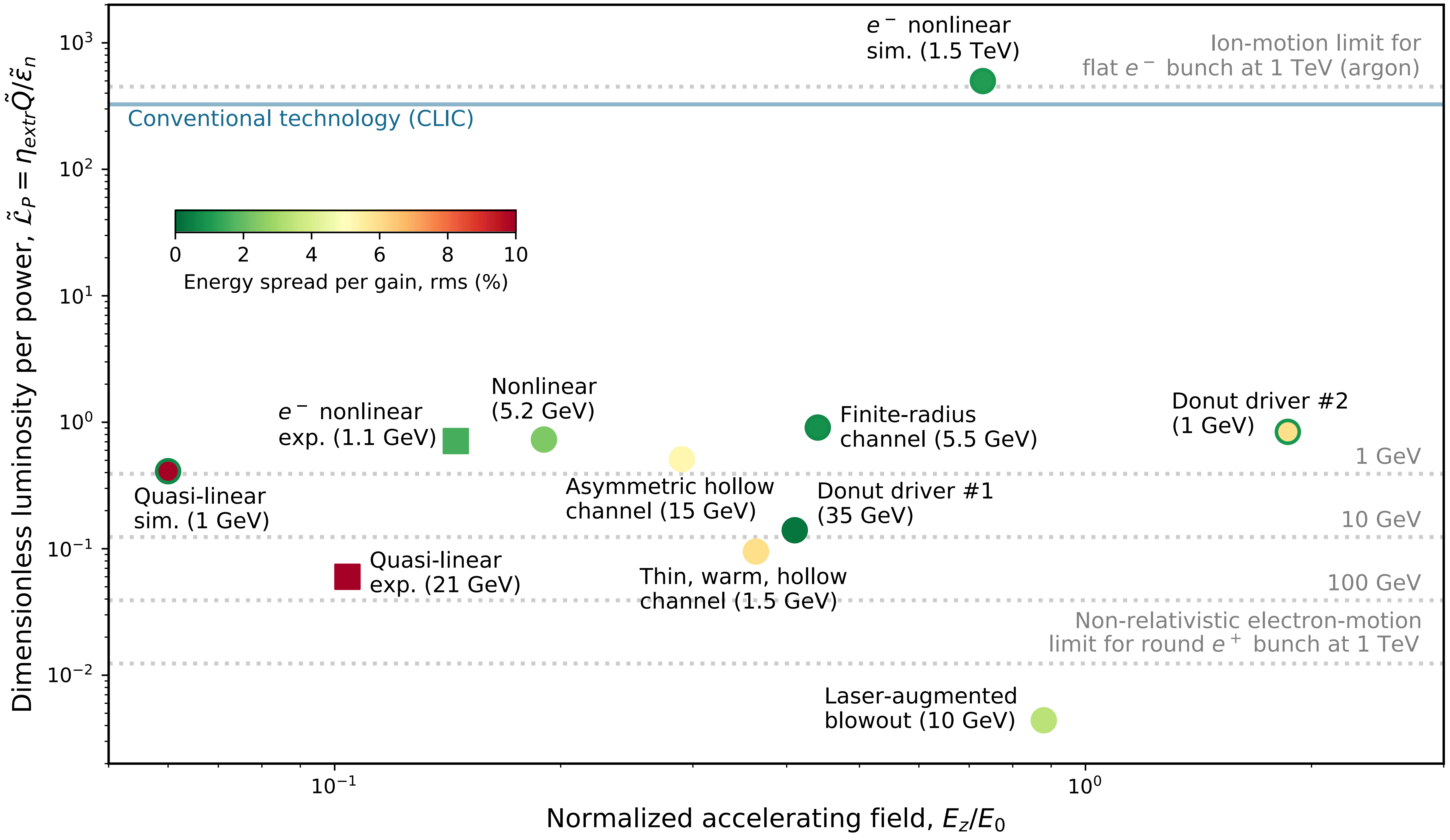
- Currently, *luminosity per power* still ~1000x below RF and e^-.
- Main challenge: *Electron motion* (equivalent to ion motion for e^-, but plasma electrons are lighter)

Comparison of proposed positron schemes (+electron schemes and RF)



Source: ***Cao, Lindstrøm et al. arXiv.2309.10495 (2023)***

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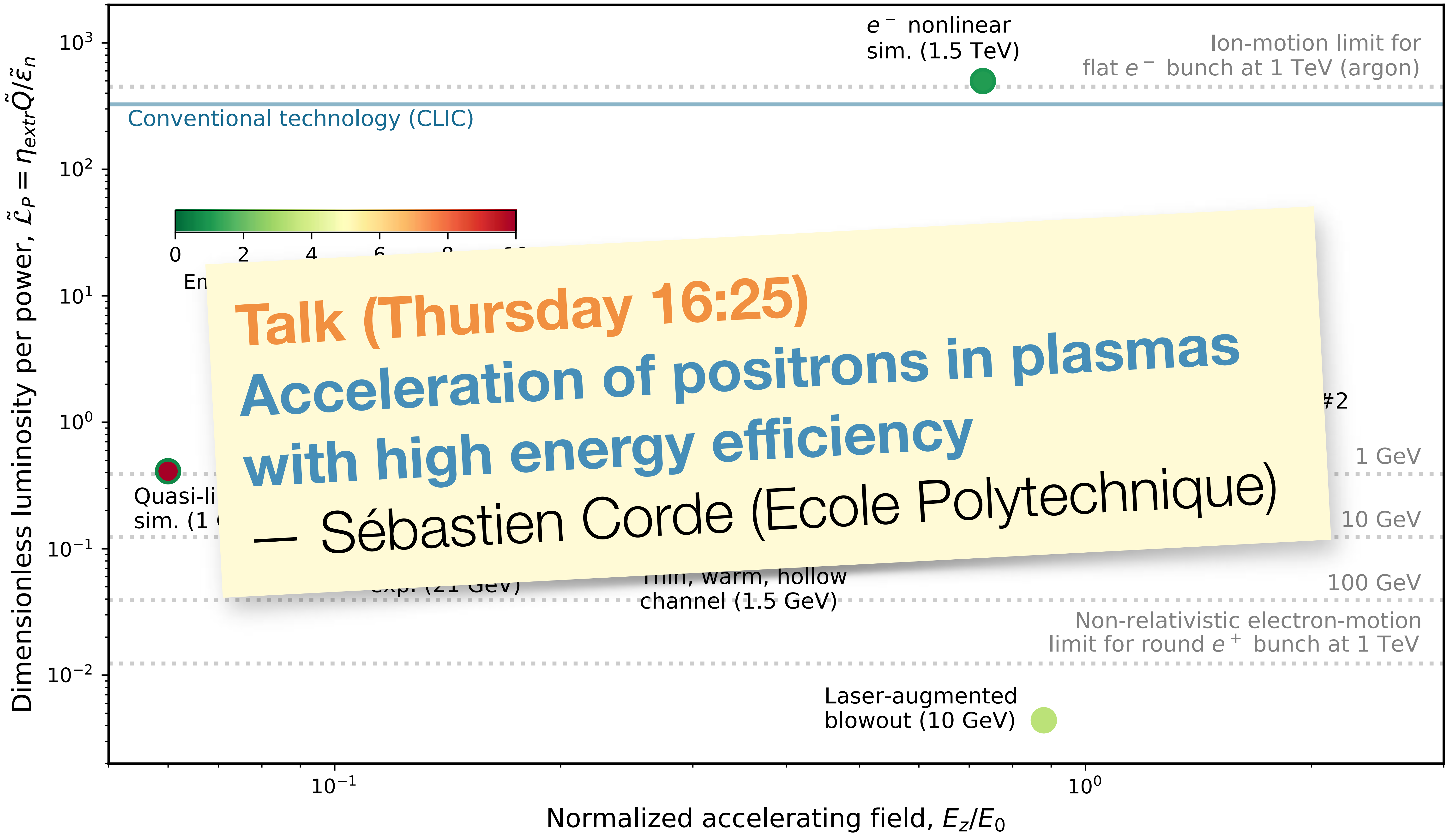


Source: ***Cao, Lindstrøm et al.*** ***arXiv.2309.10495 (2023)***

The pragmatic approach:

use **plasma** to **accelerate electrons**

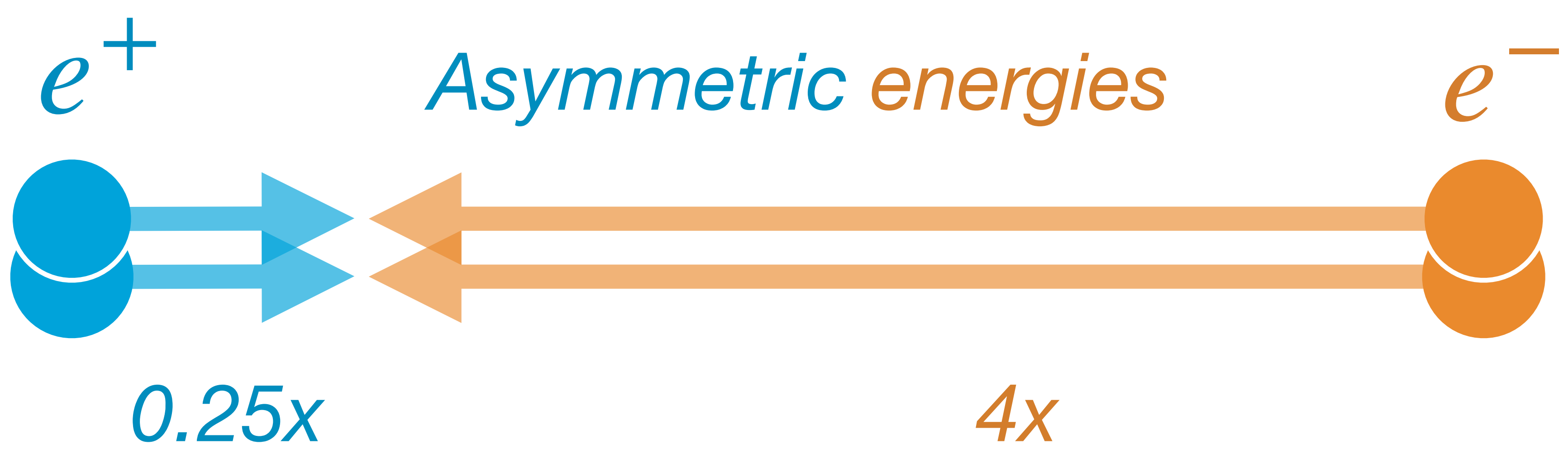
but **RF** to **accelerate positrons**

Can we use **asymmetric e+/e- energies**?

- Minimum centre-of-mass energy required for Higgs factory: **$\sqrt{s} \approx 250$ GeV**

- Electron (E_e) and positron energies (E_p) must follow: $$E_e E_p = s/4$$
  - However, the collision products are boosted (γ): $$\gamma = \frac{1}{2}\left(\frac{2E_p}{\sqrt{s}} + \frac{\sqrt{s}}{2E_p}\right)$$

- A reasonable (but not necessarily optimized) choice is:
  - Electrons (from PWFA): **E_e = 500 GeV** (4x higher)
  - Positrons (from RF accelerator): **E_p = 31 GeV** (4x lower)
  - Boost: **γ = 2.13**
    (HERA had a boost of γ ≈ 3)



Simulating asymmetric e^+/e^- collisions

> GUINEA-PIG beam–beam simulations:

E (GeV)	σ_z (μm)	N (10^{10})	ϵ_{nx} (μm)	ϵ_{ny} (nm)	β_x (mm)	β_y (mm)	$\mathcal{L}$ (μb^{-1})	$\mathcal{L}_{0.01}$ (μb^{-1})	P/P_0
125 / 125	300 / 300	2 / 2	10 / 10	35 / 35	13 / 13	0.41 / 0.41	1.12	0.92	1
31.3 / 500	300 / 300	2 / 2	10 / 10	35 / 35	3.3 / 52	0.10 / 1.6	0.93	0.71	2.13
31.3 / 500	75 / 75	2 / 2	10 / 10	35 / 35	3.3 / 52	0.10 / 1.6	1.04	0.71	2.13

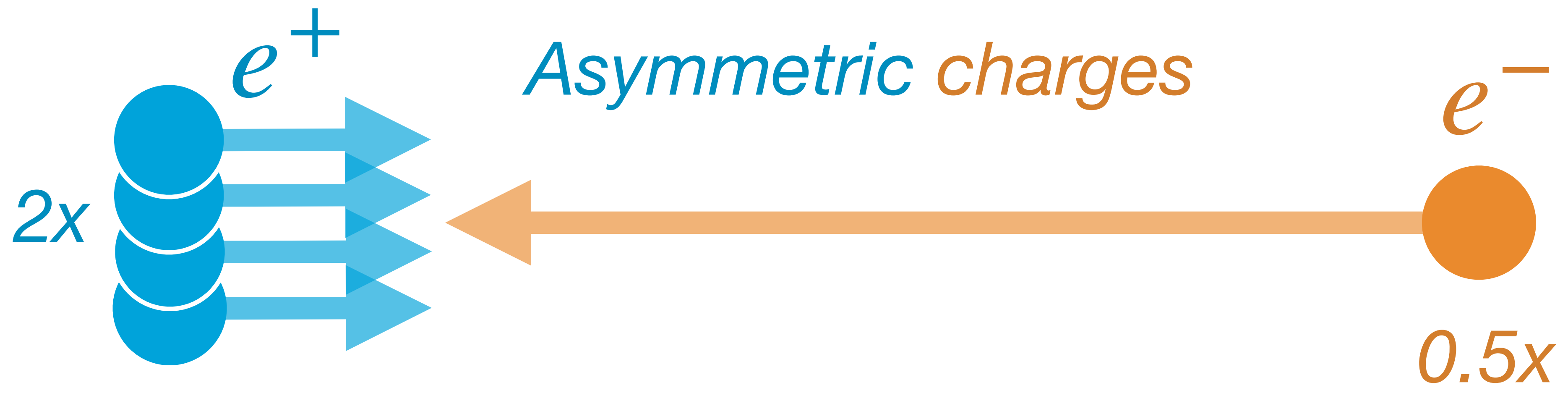
Use shorter bunches to compensate
for smaller IP beta functions

> **Asymmetric energies give similar luminosity**

> However, **more power is required** (to boost the collision products)

Mitigating the power-efficiency problem: **Asymmetric charge**

- The luminosity scales as: $\mathscr{L} \sim N_p N_e$
- Can we use more (low-energy) positrons and less (high-energy) electrons? **Yes**
  - Power usage increase: $$\frac{P}{P_0} = \frac{N_e E_e + N_p E_p}{N\sqrt{s}}$$



- **Unchanged power usage if $N_e/N_p = E_p/E_e$** (here: 4x more e^+, 4x less e^-)
  - But, producing positrons is problematic—instead use **2x more e^+, 2x less e^-**

E (GeV)	σ_z (µm)	N (10^{10})	ϵ_{nx} (µm)	ϵ_{ny} (nm)	β_x (mm)	β_y (mm)	$\mathcal{L}$ (µb^{-1})	$\mathcal{L}_{0.01}$ (µb^{-1})	P/P_0
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31.3 / 500	75 / 75	2 / 2	10 / 10	35 / 35	3.3 / 52	0.10 / 1.6	1.04	0.71	2.13
31.3 / 500	75 / 75	4 / 1	10 / 10	35 / 35	3.3 / 52	0.10 / 1.6	1.04	0.60	1.25

Going *all-in*: **Asymmetric emittances ease beam-quality needs**

- *Geometric* emittance scales as (energy)$^{-1}$ — how to achieve same beam size at IP?
- e^+ **(lower energy) must have smaller IP beta function**: 3.3/0.1 mm (like CLIC)
  - Conversely, electrons can have a larger IP beta function
- **Better yet — increase the e^- (*normalised*) emittance.**
  - Significantly reduces emittance requirements from PWFAs!

E (GeV)	σ_z (µm)	N (10^{10})	ϵ_{nx} (µm)	ϵ_{ny} (nm)	β_x (mm)	β_y (mm)	$\mathcal{L}$ (µb^{-1})	$\mathcal{L}_{0.01}$ (µb^{-1})	P/P_0
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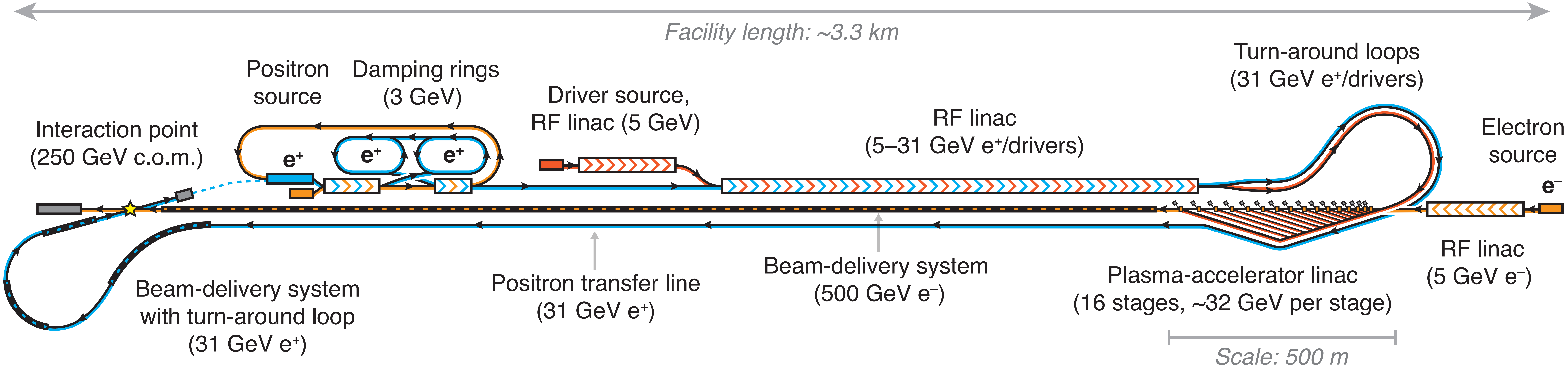
31.3 / 500	75 / 75	4 / 1	10 / 40	35 / 140	3.3 / 13	0.10 / 0.41	1.01	0.58	1.25
31.3 / 500	75 / 75	4 / 1	10 / 80	35 / 280	3.3 / 6.5	0.10 / 0.20	0.94	0.54	1.25
31.3 / 500	75 / 75	4 / 1	10 / 160	35 / 560	3.3 / 3.3	0.10 / 0.10	0.81	0.46	1.25

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory

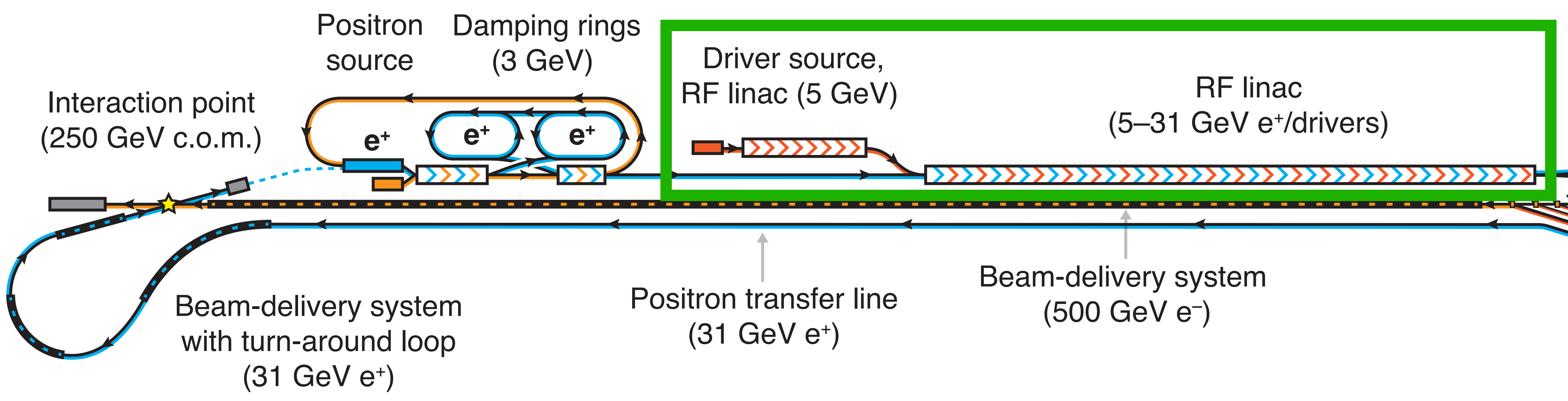


Source: Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

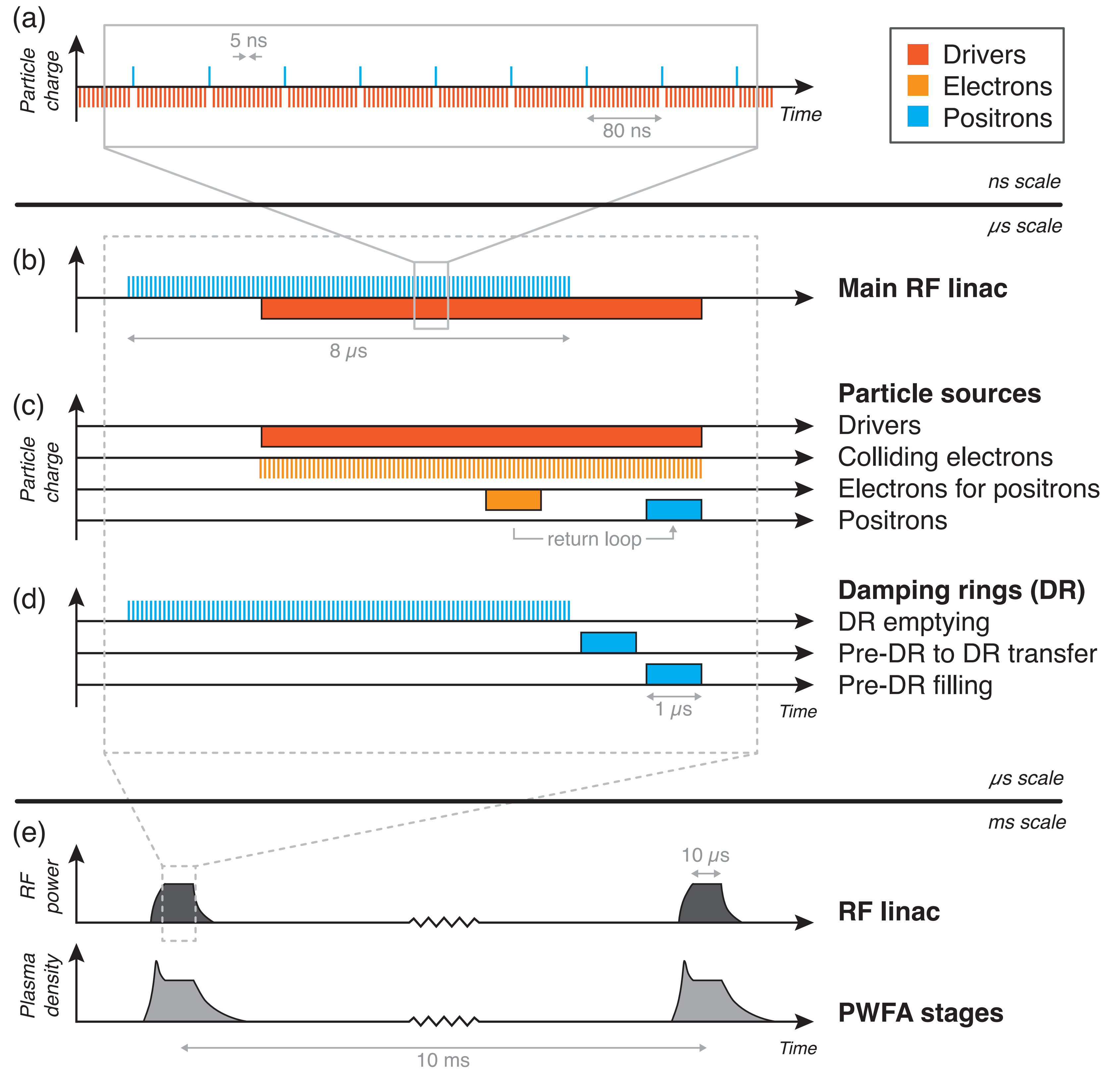
- Beam-driven: Use e^+ RF linac for producing e^- drivers
- Overall footprint: ~3.3 km
  - Length dominated by e^- beam-delivery system
  - Fits in most major particle-physics laboratories

The foundation: **A main RF linac**

RF linac parameters		
Average gradient	MV/m	25
Wall-plug-to-beam efficiency	%	50
RF power usage	MW	47.5
Peak RF power per length	MW/m	21.4
Cooling req. per length	kW/m	20



- RF linac length: ~1.3 km
- Assumes 50% efficient acceleration
- Gradient: 25 MV/m
- Bunch-train pattern must be compatible with PWFA stages (constant density required):
  - NCRF? Burst-mode (100 bunches @ 100 Hz)
  - SCRF? Continuous wave (10 kHz)



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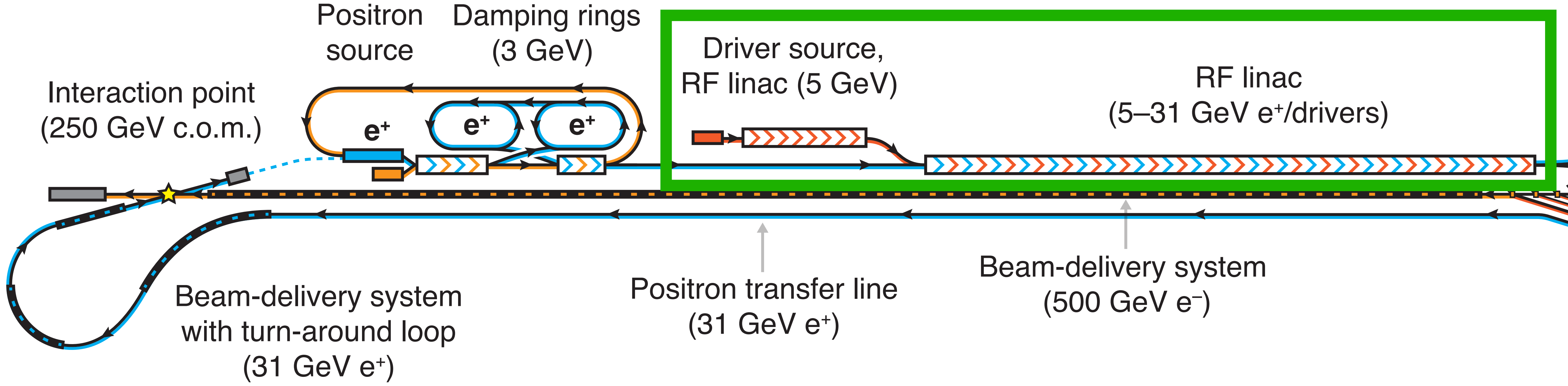

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- Bunch-train pattern m… stages (constant dens…
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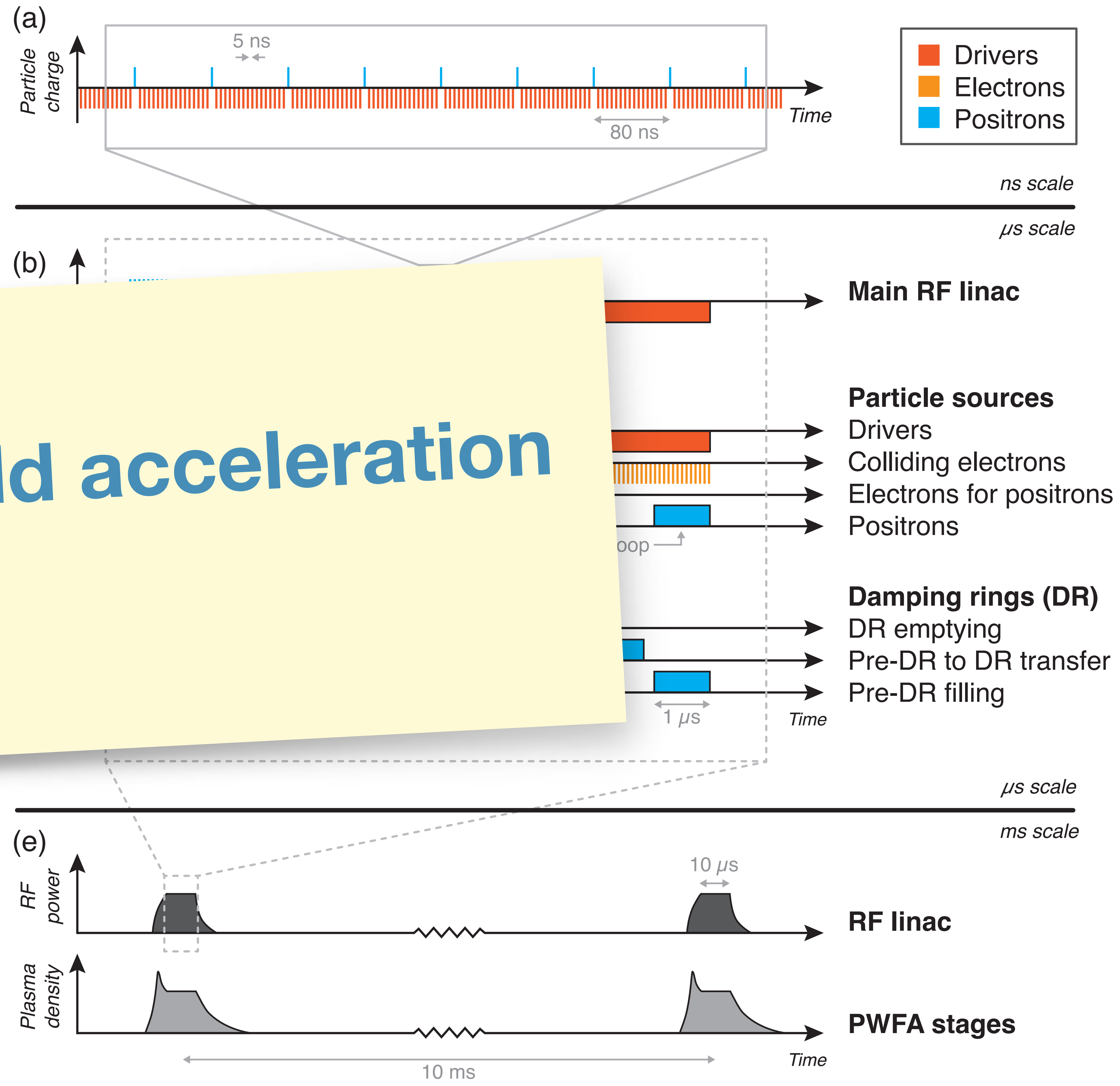
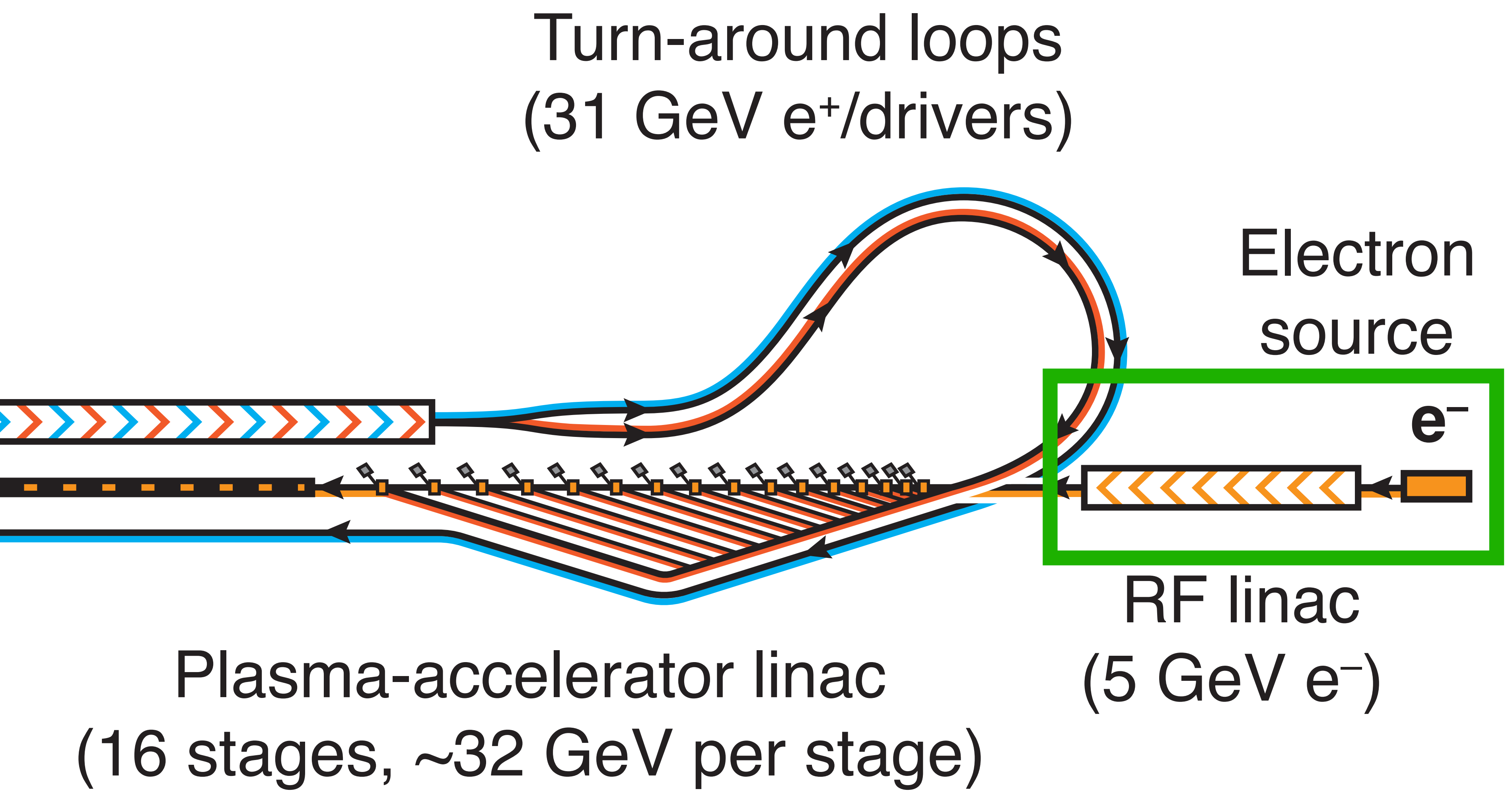
Talk (Thursday 16:25)
Beam-driven plasma wakefield acceleration at Megahertz repetition rates
— Gregor Loisch (DESY)

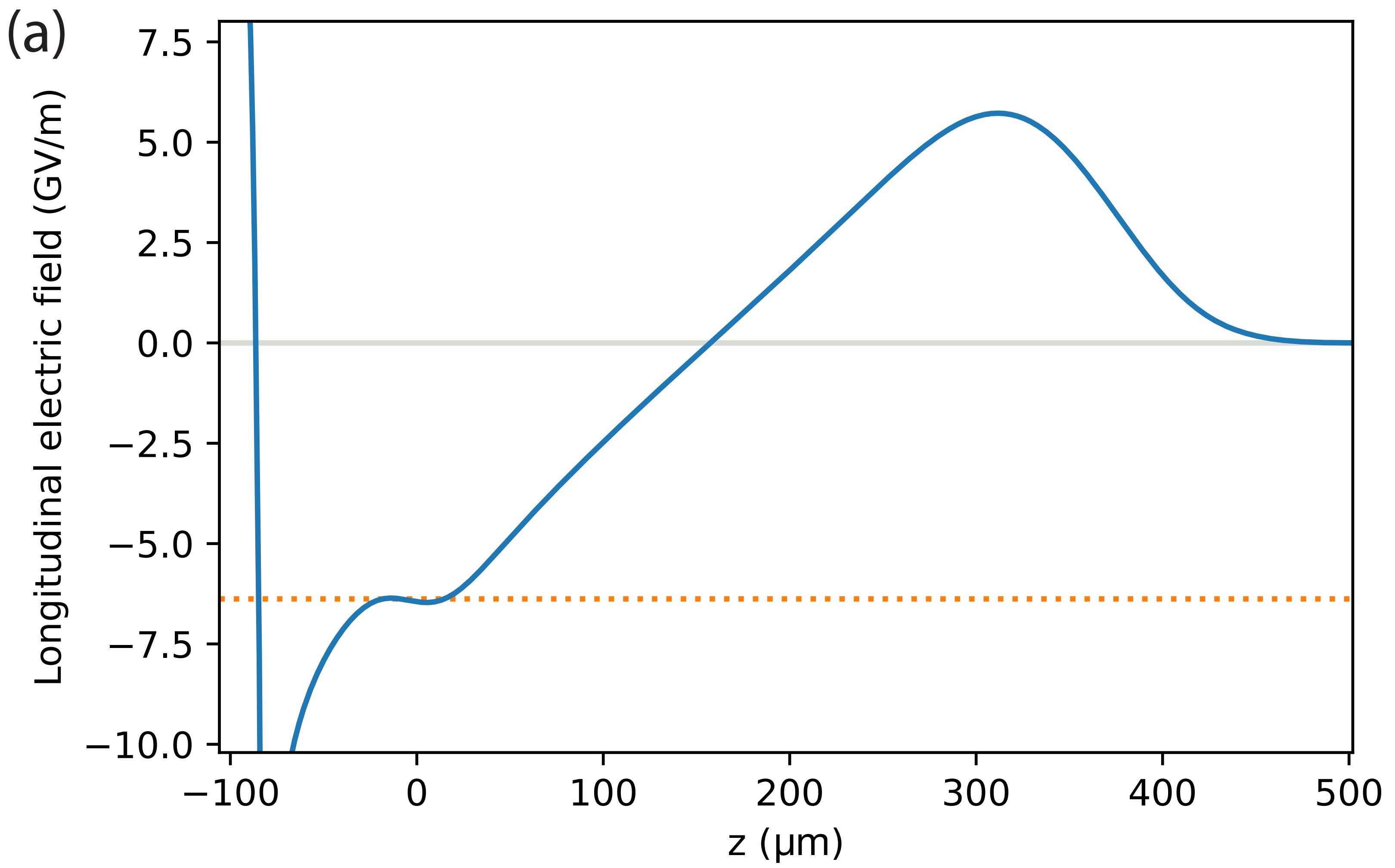


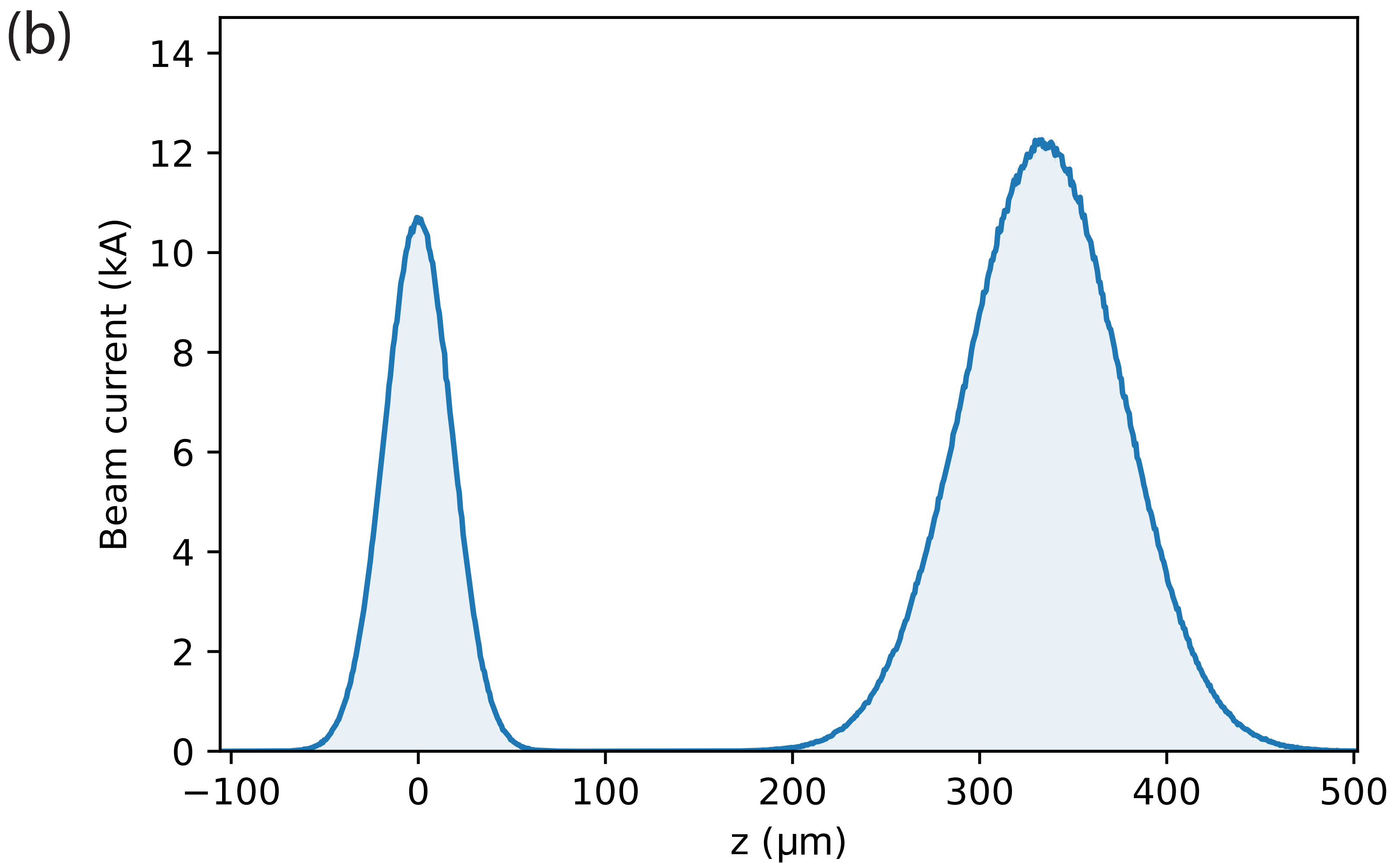
The novelty: **A multistage plasma-based linac**

- > Length: 16 PWFA stages (5-m long): ~400 m total length
- > Gradient: 6.4 GV/m (in plasma) — 1.2 GV/m (average)
- > Efficiency: 38% = 72% depletion, 53% wake extraction
- > No damping ring required due to high-emittance electrons



PWFA linac parameters		
Number of stages		16
Plasma density	cm^{-3}	1.5×10^{16}
In-plasma acceleration gradient	GV/m	6.4
Average gradient (incl. optics)	GV/m	1.2
Length per stage[a]	m	5
Energy gain per stage[a]	GeV	31.9
Initial injection energy	GeV	5
Driver energy	GeV	31.25
Driver bunch population	10^{10}	2.7
Driver bunch length (rms)	μm	27.6
Driver average beam power	MW	21.4
Driver bunch separation	ns	5
Driver-to-wake efficiency	%	74
Wake-to-beam efficiency	%	53
Driver-to-beam efficiency	%	39
Wall-plug-to-beam efficiency	%	19.5
Cooling req. per stage length	kW/m	100





Simulated with Wake-T
Plasma density: 7 x 10^{15} cm^{-3}
Driver/witness charge: 4.3/1.6 nC

Rough cost estimates for HALHF

- Scaled from existing collider projects (ILC/CLIC) where possible — not exact.
  - European accounting (2022 $): **~$1.9B** (**~1/4 of ILC TDR cost** @ 250 GeV)
  - US accounting ("TPC"): **$2.3–3.9B** ($4.6B from ITF model for RF accelerators)
- Dominated by conventional collider costs (97%) — **PWFA linac only ~3% of the cost**

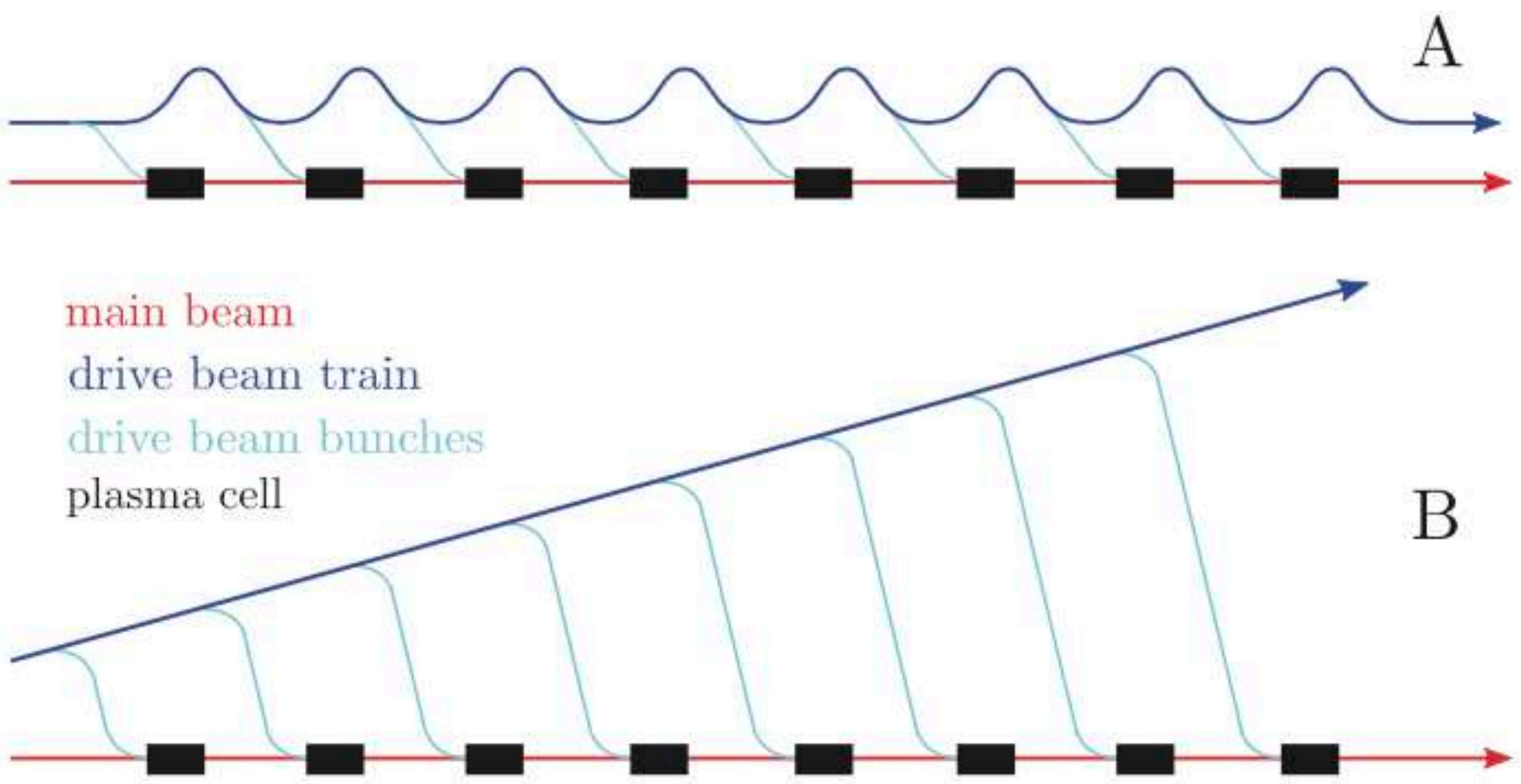
Subsystem	Original cost (MILCU)	Comment	Scaling factor	HALHF cost (MILCU)	Fraction
Particle sources, damping rings	430	CLIC cost [76], halved for e^+ damping rings only[a]	0.5	215	14%
RF linac with klystrons	548	CLIC cost, as RF power is similar	1	548	35%
PWFA linac	477	ILC cost [46], scaled by length and multiplied by 6[b]	0.1	48	3%
Transfer lines	477	ILC cost, scaled to the ~4.6 km required[c]	0.15	72	5%
Electron BDS	91	ILC cost, also at 500 GeV	1	91	6%
Positron BDS	91	ILC cost, scaled by length[d]	0.25	23	1%
Beam dumps	67	ILC cost (similar beam power) + drive-beam dumps[e]	1	80	5%
Civil engineering	2,055	ILC cost, scaled to the ~10 km of tunnel required	0.21	476	31%
			Total	1,553	100%

- Estimated **power usage is ~100 MW** (similar to ILC and CLIC):
  - 21 MW beam power + 27 MW losses + 2×10 MW damping rings + 50% for cooling/etc.

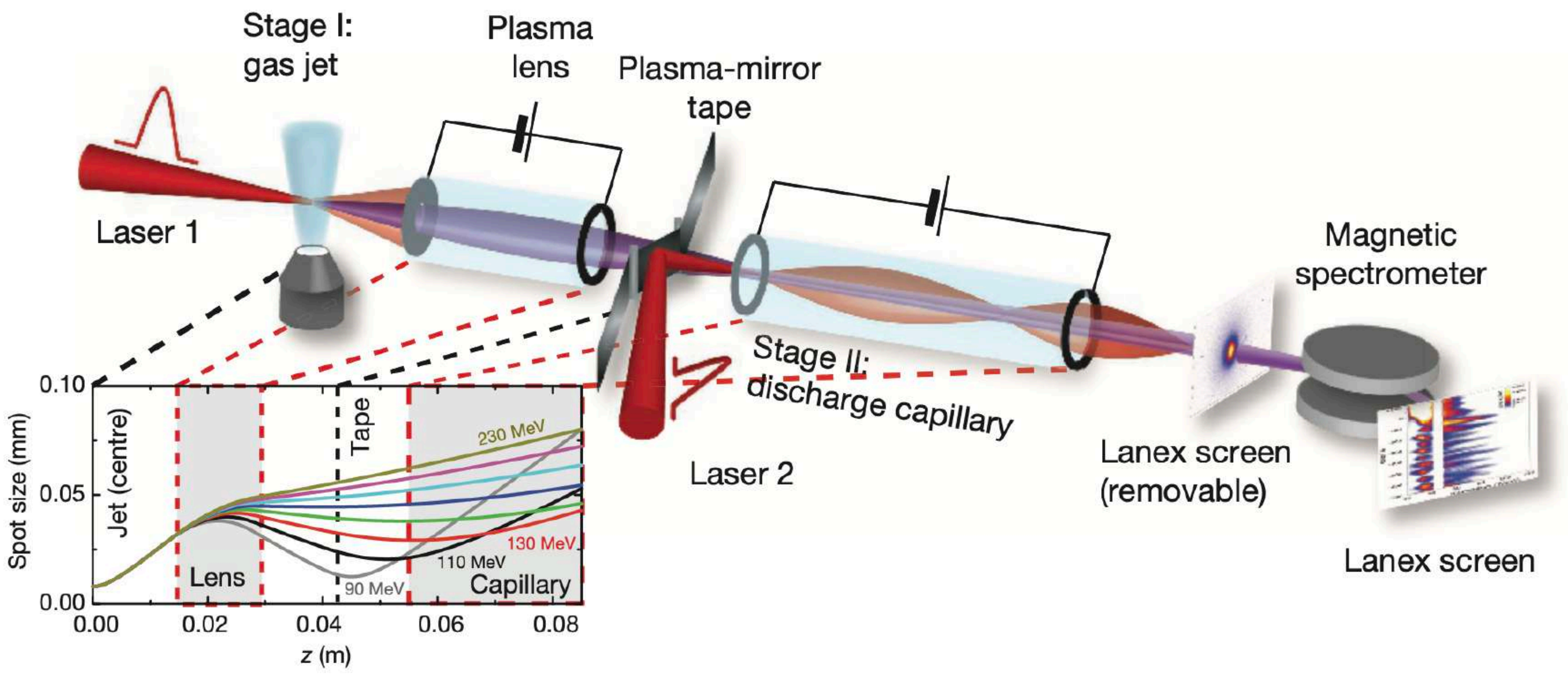
Innovations required: **Plasma-accelerator R&D**

- Toward high energy:
  - Compact staging optics with quality preservation
  - Multi-stage driver distribution

Talk **(Thursday 18:25)**
Readiness of electron plasma linacs for a collider application
— Erik Adli (University of Oslo)



From: Pfingstner et al. (Proc. IPAC 2016)



From: Steinke et al., Nature 530, 190 (2016).

Innovations required: **Plasma-accelerator R&D**

- > Toward high energy:
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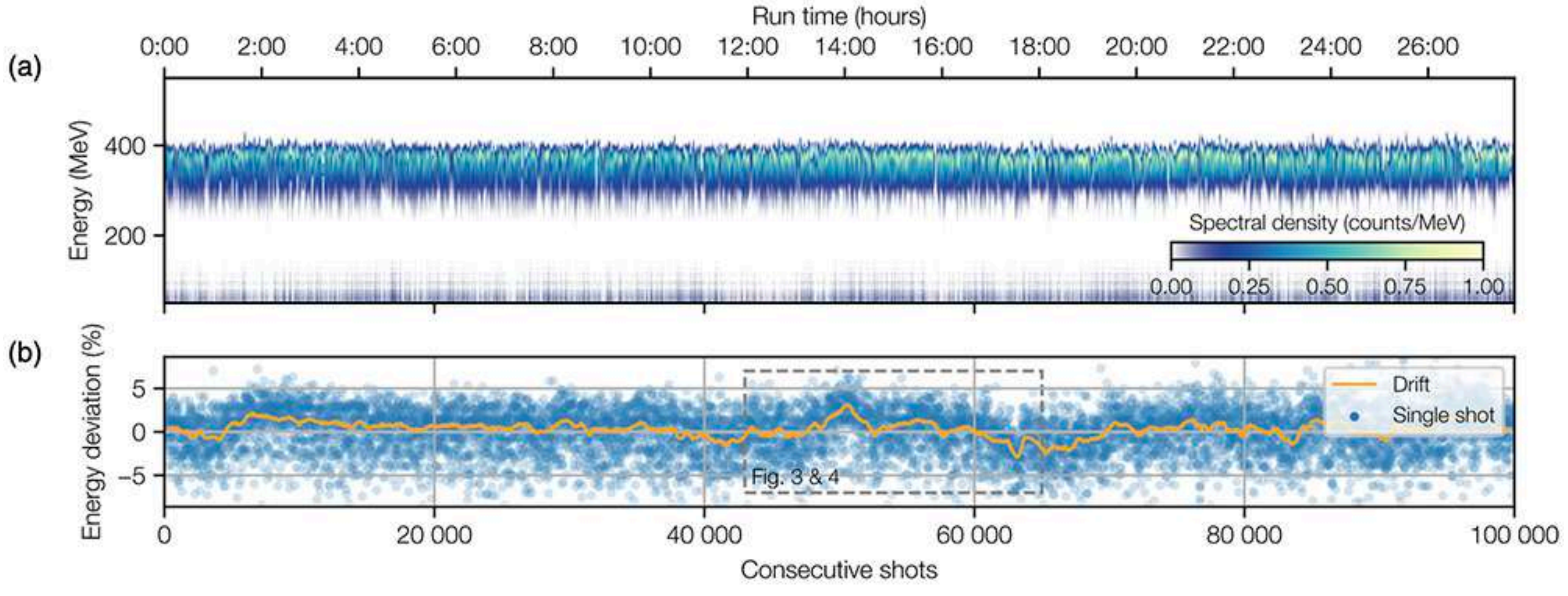
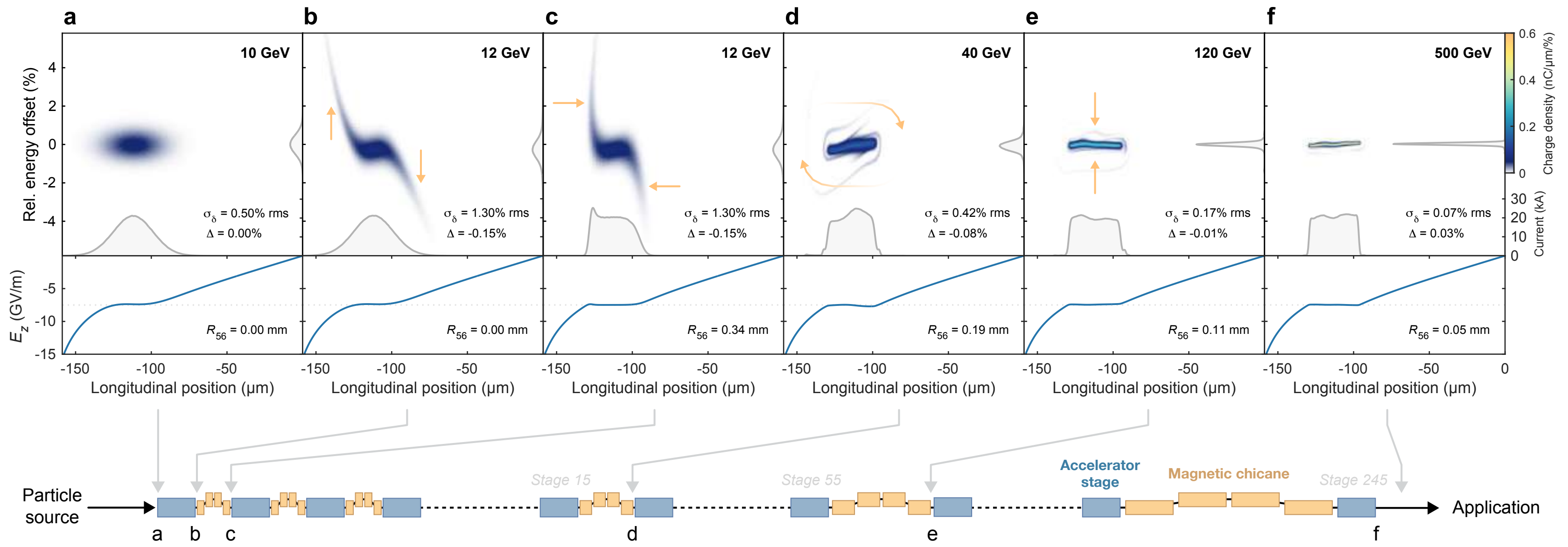
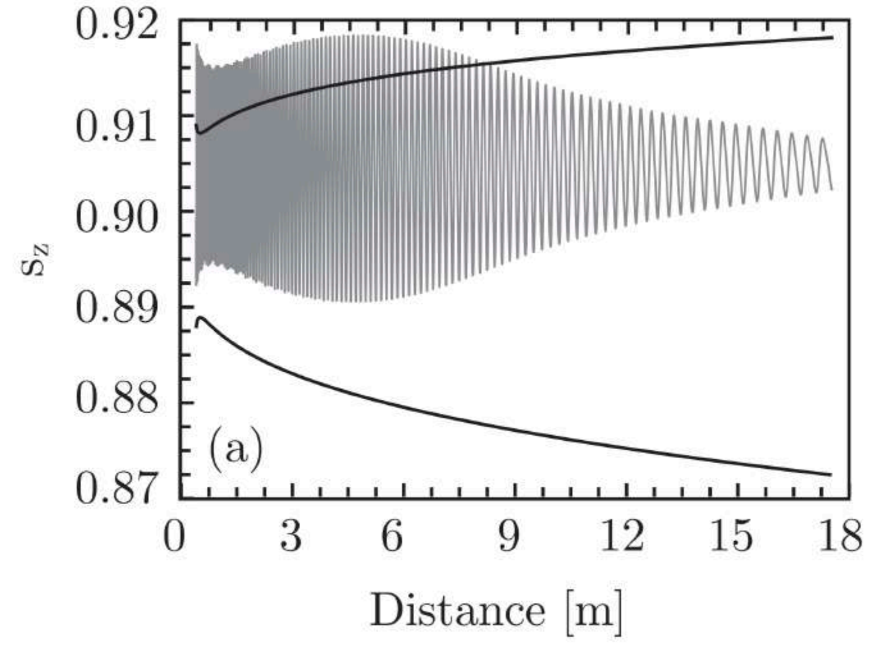
  - > Multi-stage driver distribution
- > Toward high beam quality:
  - > Transverse and longitudinal stability
  - > Emittance and energy-spread preservation
  - > Spin-polarization preservation



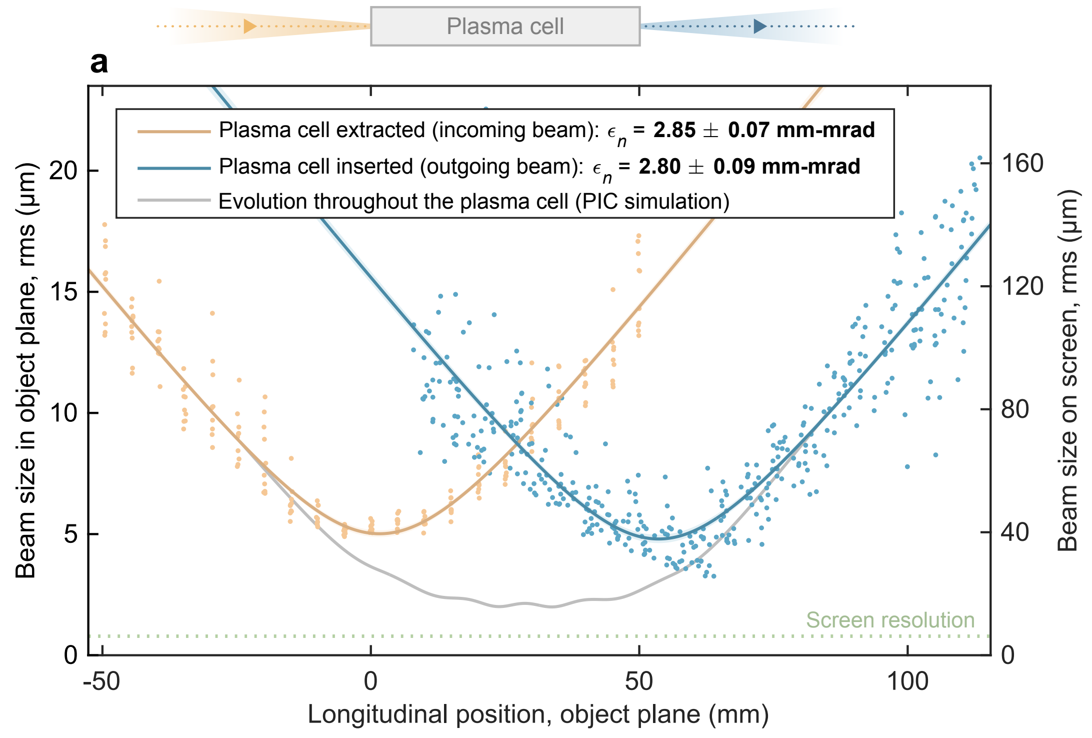
From: Maier et al., Phys. Rev. X 10, 031039 (2020).



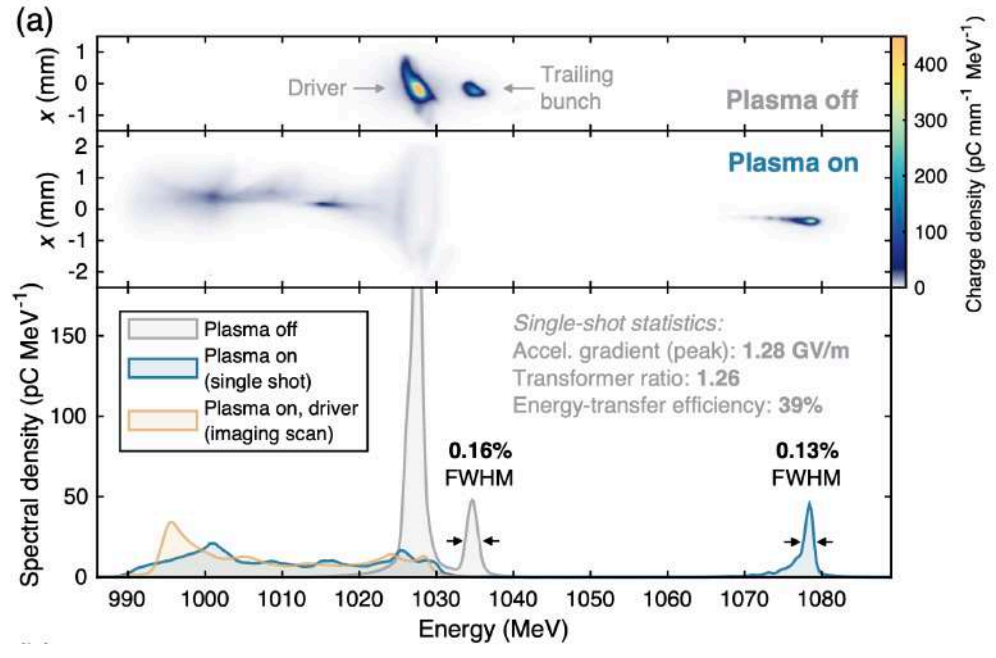
From: Lindstrøm (arXiv: 2104.14460).



From: Vieira et al. PR-STAB 14, 071303 (2011)



From: Lindstrøm et al. (submitted)



From: Lindstrøm et al., PRL 126, 014801 (2021)

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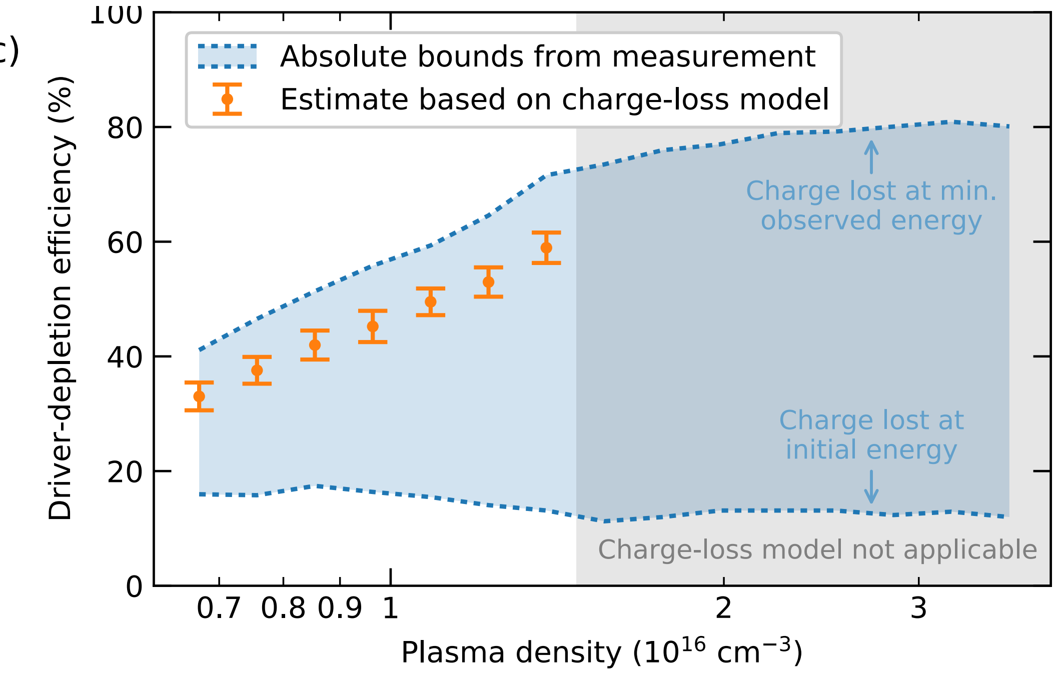
  - > Multi-stage driver distribution
- > Toward high beam quality:
  - > Transverse and longitudinal stability
  - > Emittance and energy-spread preservation
  - > Spin-polarization preservation
- > Toward high beam power:
  - > High-overall efficiency (wall-plug to beam)
  - > Repetition rate
  - > Plasma-cell cooling

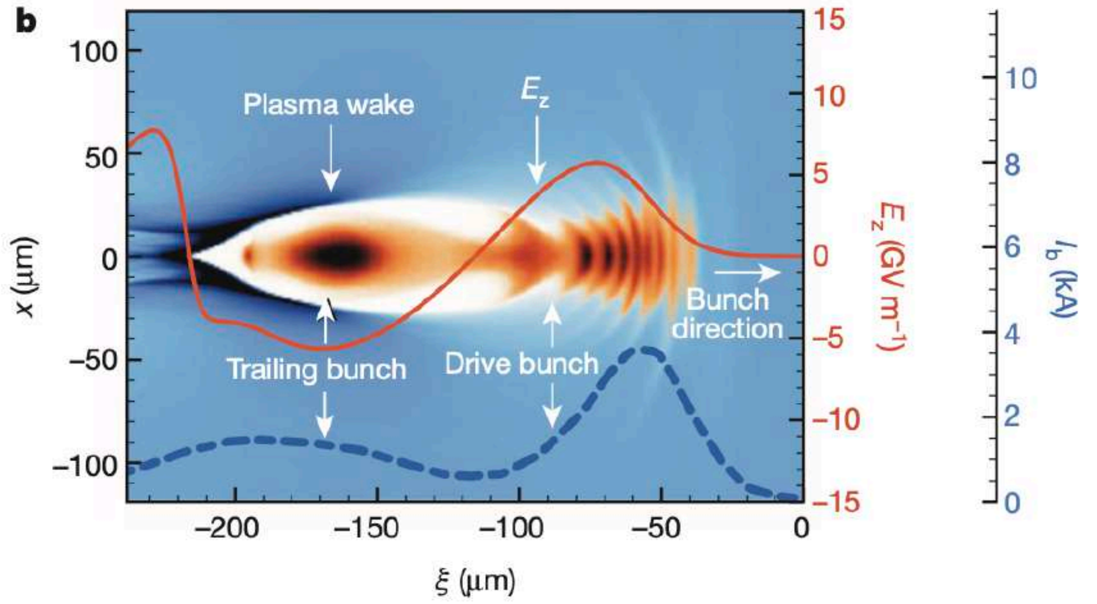
Depletion efficiency

(Must be achieved simultaneously)

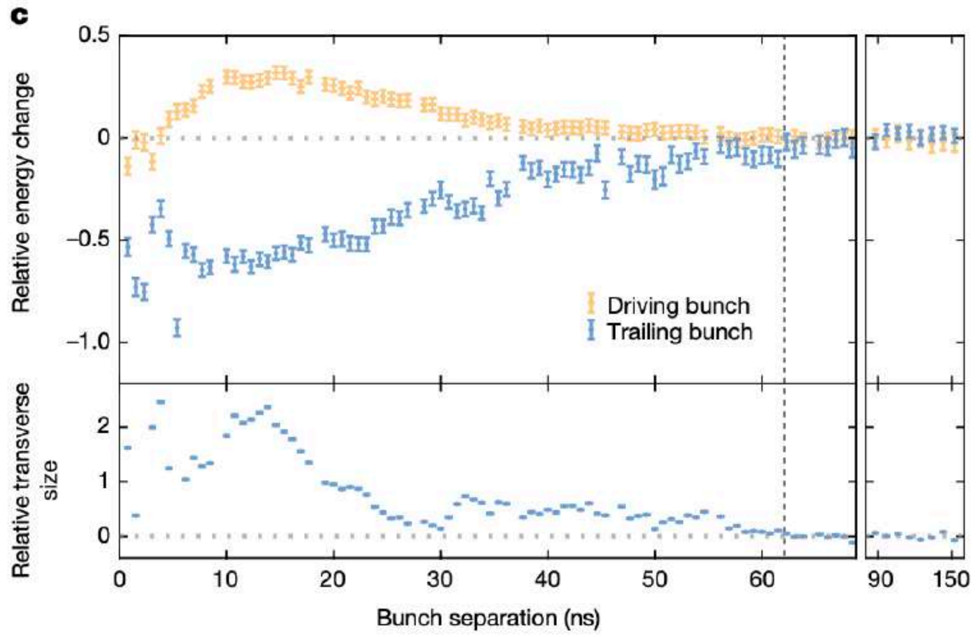
Extraction efficiency



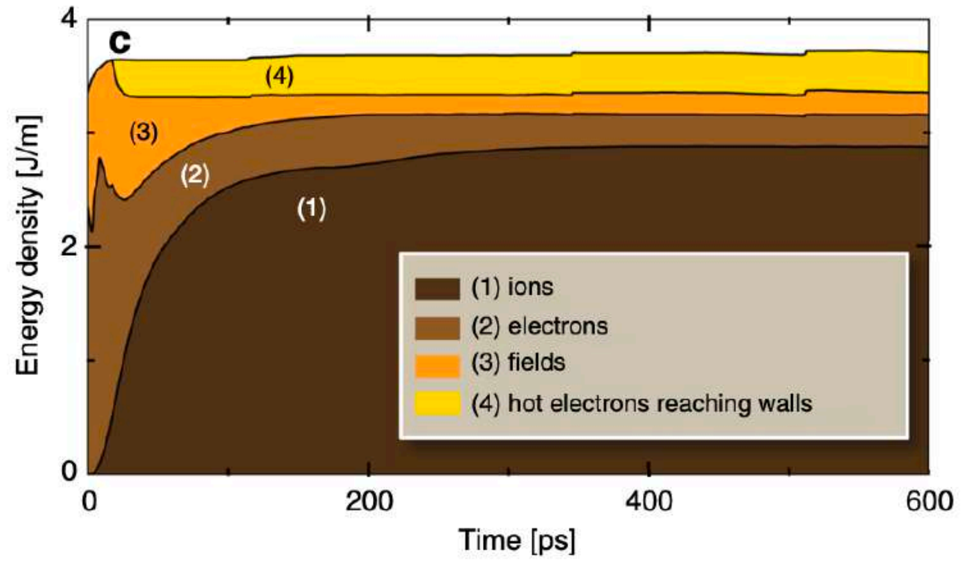
From: Peña et al. (arXiv:2305.09581)



From: Litos et al., Nature 515, 92 (2014).



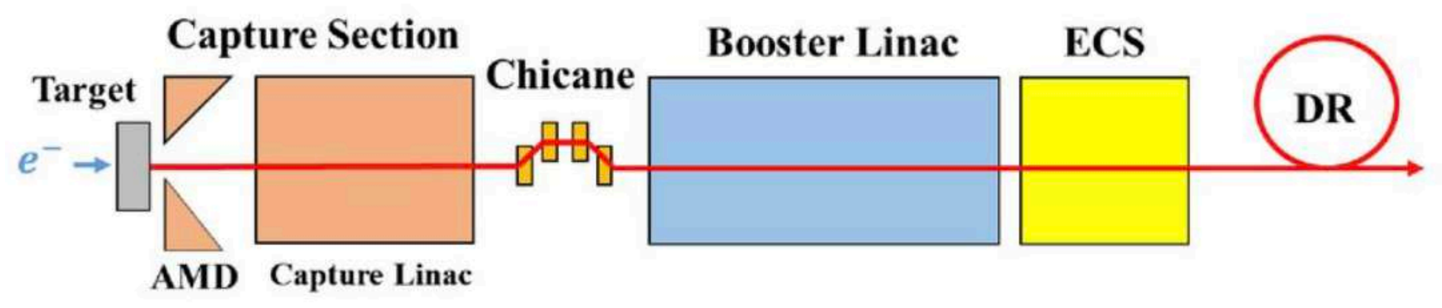
From: D'Arcy et al., Nature 603, 58 (2022).



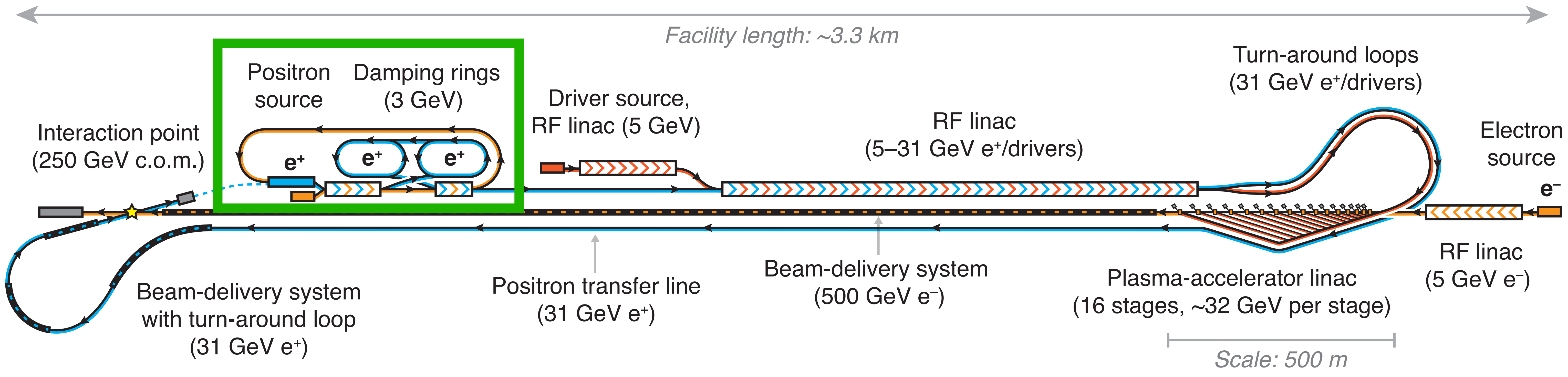
From: Zgadzaj et al., Nat. Commun. 11, 4753 (2020)

Innovations required: **Conventional accelerator R&D**

> High-charge positron source (2x charge compared to ILC)



Sketch of ILC positron source



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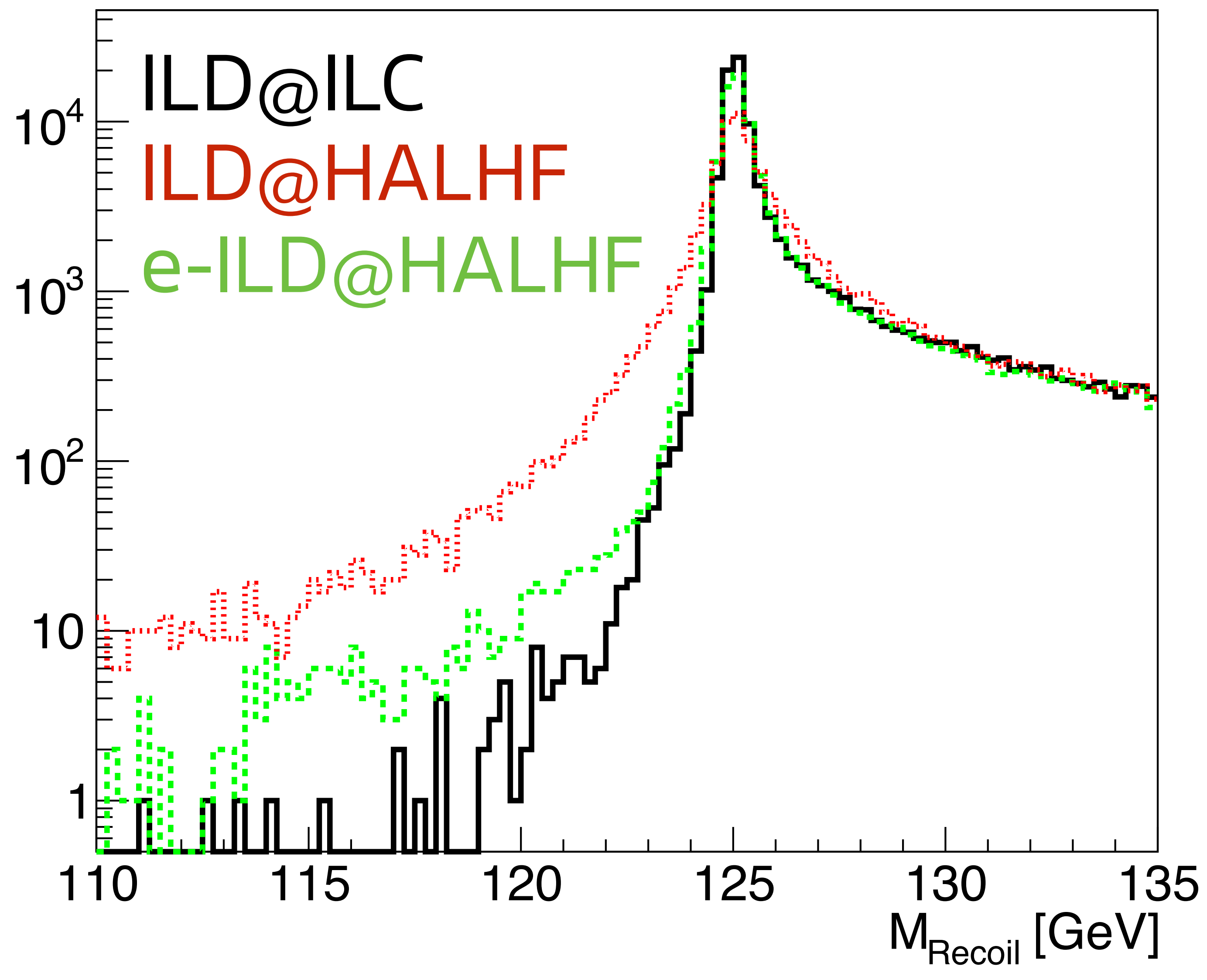
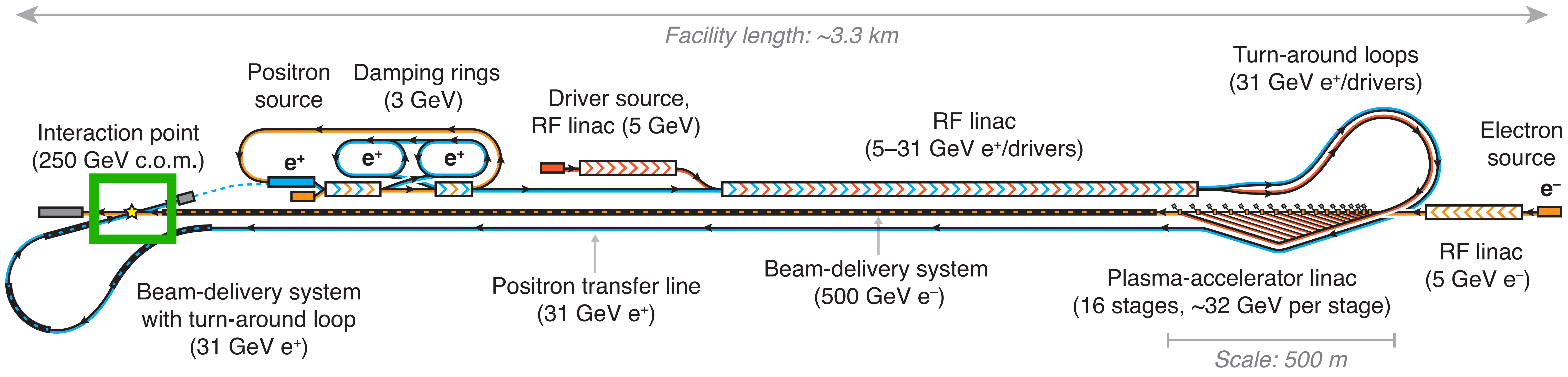
- High-charge positron source (2x charge compared to ILC)
- Detector optimised for asymmetric energies



Source: A. Laudrain, talk at EPS-HEP Conference (2023)



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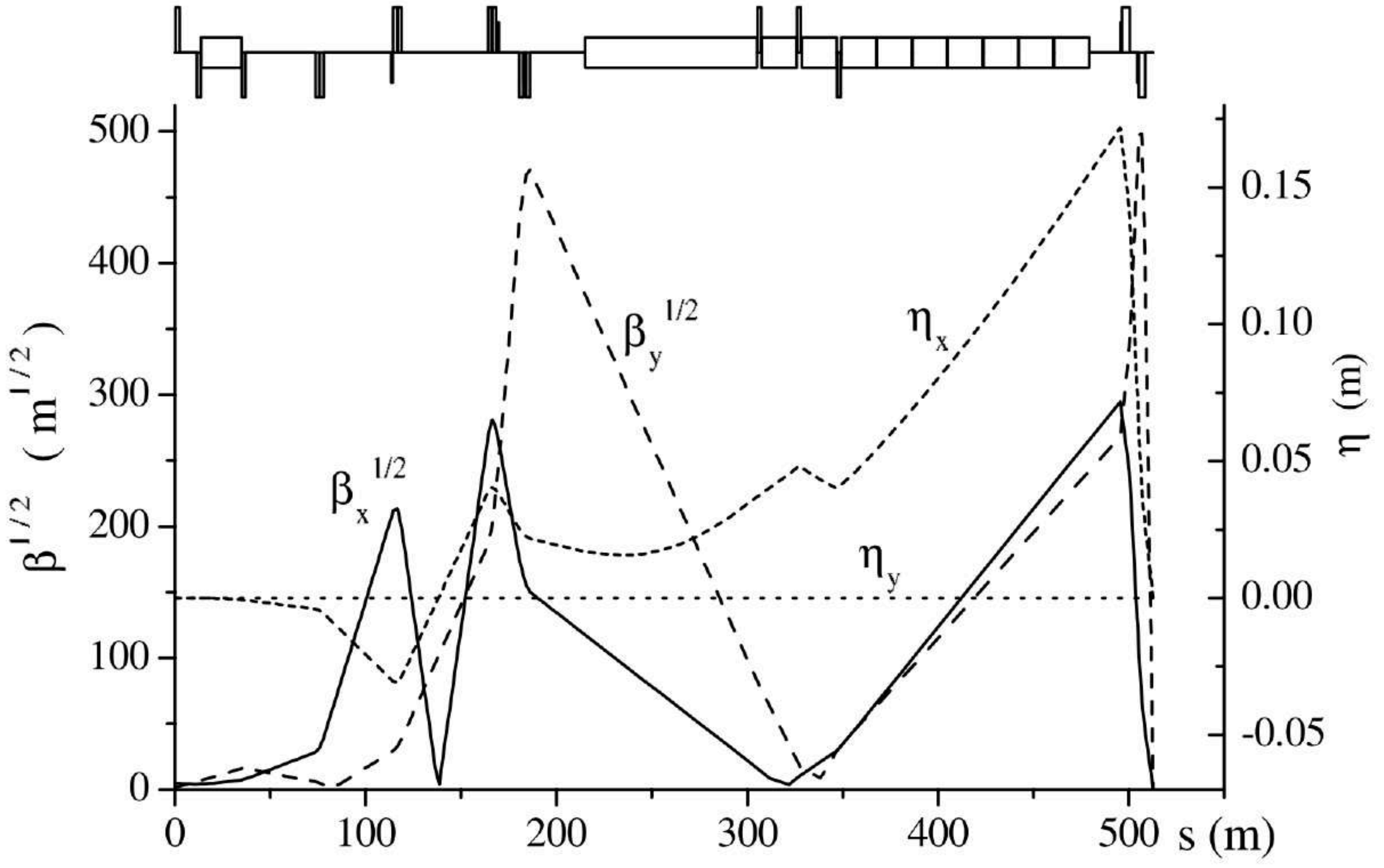
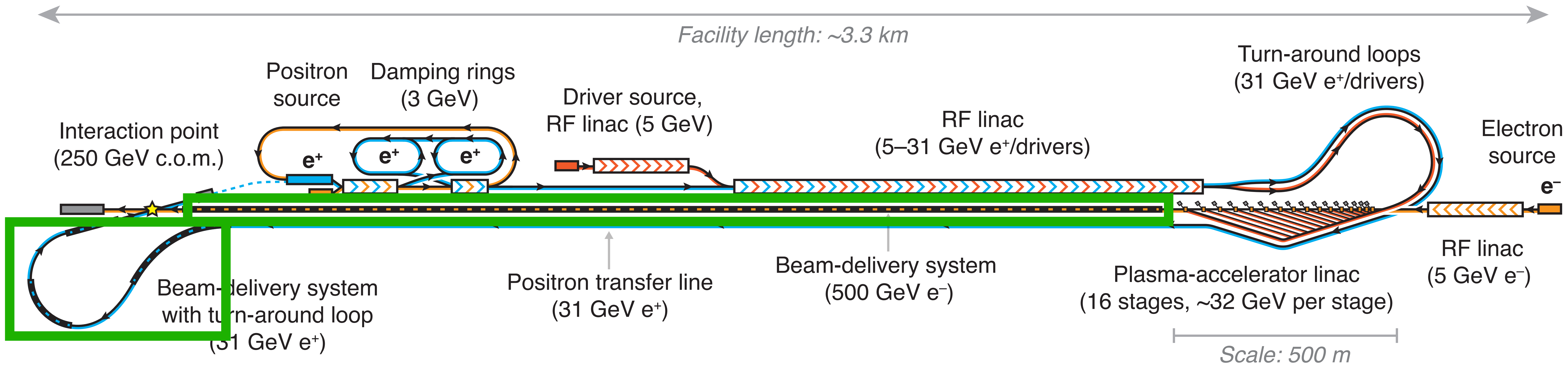
- High-charge positron source (2x charge compared to ILC)
- Detector optimised for asymmetric energies
- Beam-delivery systems:
  - Small beta functions (3.3 x 0.1 mm)
  - Could it be shorter since the emittance is much higher? (would reduce HALHF footprint considerably)



*From: Raimondi & Seryi, PRL **86**, 3779 (2001)*



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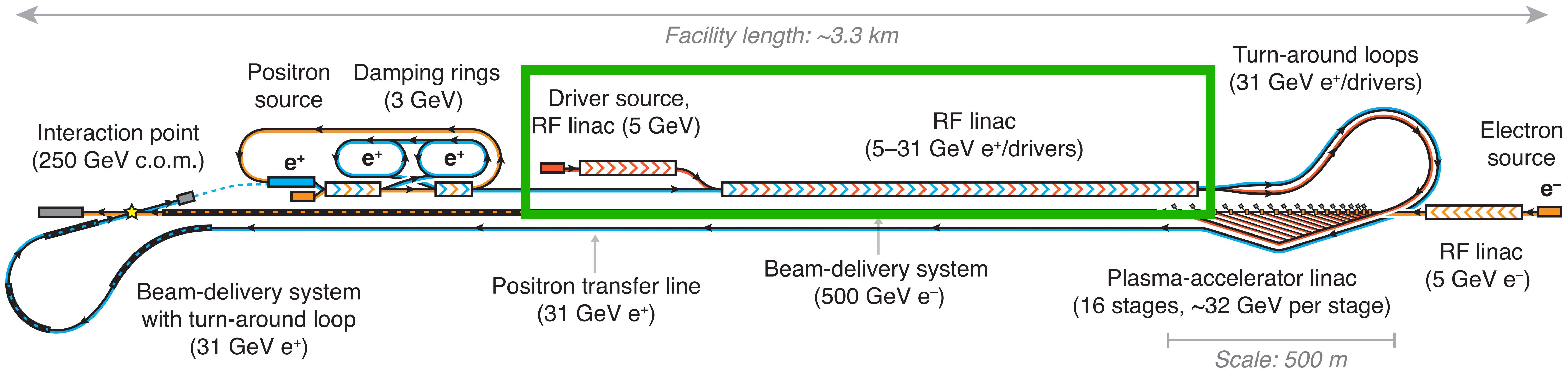
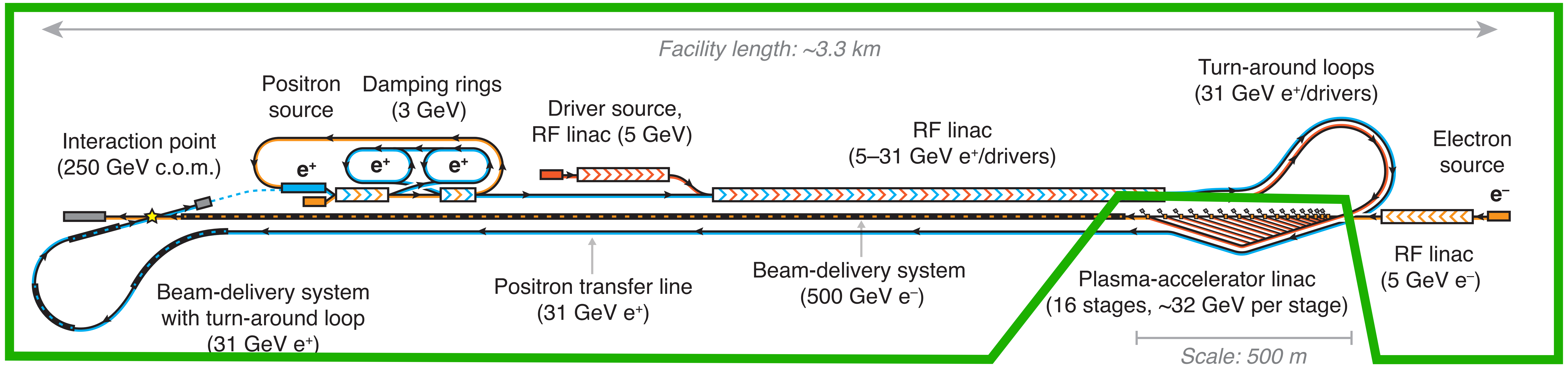
- High-efficiency (heavily beam loaded) RF linac with PWFA-compatible beams



Innovations required: **Conventional accelerator R&D**

- High-charge positron source (2x charge compared to ILC)
- Detector optimised for asymmetric energies
- Beam-delivery systems:
  - Small beta functions (3.3 x 0.1 mm)
  - Could it be shorter since the emittance is much higher? (would reduce HALHF footprint considerably)
- High-efficiency (heavily beam loaded) RF linac with PWFA-compatible beams

- *In short:*
  Conventional accelerator expertise is required



Rough timeline for HALHF (and beyond)

- Short term *(0–5 ys):* Pre-CDR (feasibility study) necessary to find self-consistent parameters
- *Near term (10–15 ys):* Tech. demonstrator — **strong-field QED** and/or an **X-ray FEL**
- *Long term (15–25 ys):* Delivery of HALHF — **intense R&D required**

Timeline (approximate/aspirational)				
0–5 years	**5–10 years**	**10–15 years**	**15–25 years**	**25+ years**
Pre-CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** Scalable staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25–100 GeV e^-)	*(Facility upgrade)*	Legend: *Feasibility study*; *R&D (exp. & theory)*; *HEP facility (earliest start of construction)*
	Demonstration of: High wall-plug efficiency (e^- drivers), preserved beam quality & spin polarization, high rep. rate, plasma temporal uniformity & cell cooling		**Higgs factory (HALHF)** Asymmetric, plasma–RF hybrid collider (250–380 GeV c.o.m.)	*(Facility upgrade)*
	Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser drivers), ultra-low emittances, energy recovery schemes, compact beam-delivery systems			**Multi-TeV e^+–e^-/γ–γ collider** Symmetric, all-plasma-based collider (> 2 TeV c.o.m.)

- *Beyond:* Upgrade path toward multi-TeV — **gamma–gamma collider?**
  - (Improve emittance, upgrade energy reach, build another electron arm)

Key areas of R&D for HALHF

- Conventional accelerator R&D:
  - High-charge positron source
  - Conventional e^+/driver linac
  - Beam delivery system
  - Asymmetric detector/physics studies
- Plasma-accelerator R&D:
  - High beam quality
  - High-average-power plasma stages
  - Staging to high energy

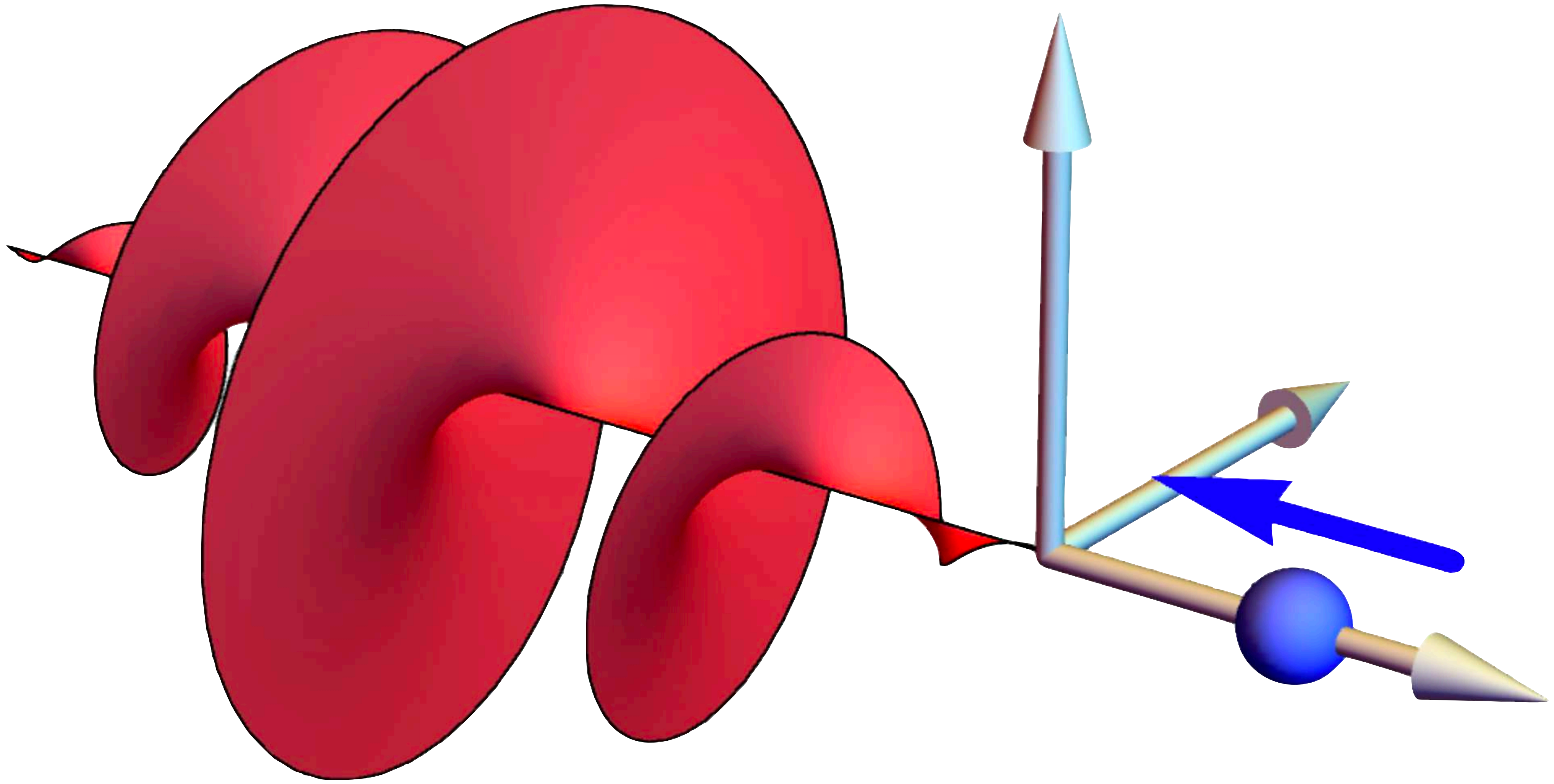
X-ray FEL: Possible mid-term application requiring high energy, quality, and rep rate

Image source: G. Stewart/SLAC.

ERC CoG application
High-Average-Power Plasma-Wakefield Studies And Applications
— Richard D'Arcy (University of Oxford, DESY)

Stepping stone: **A near-term application to strong-field QED**

- Strong-field QED experiments require:
  - High energy (*staging*) and high stability (*self-correction*)
  - But not high rep. rate, power, beam quality or polarization.

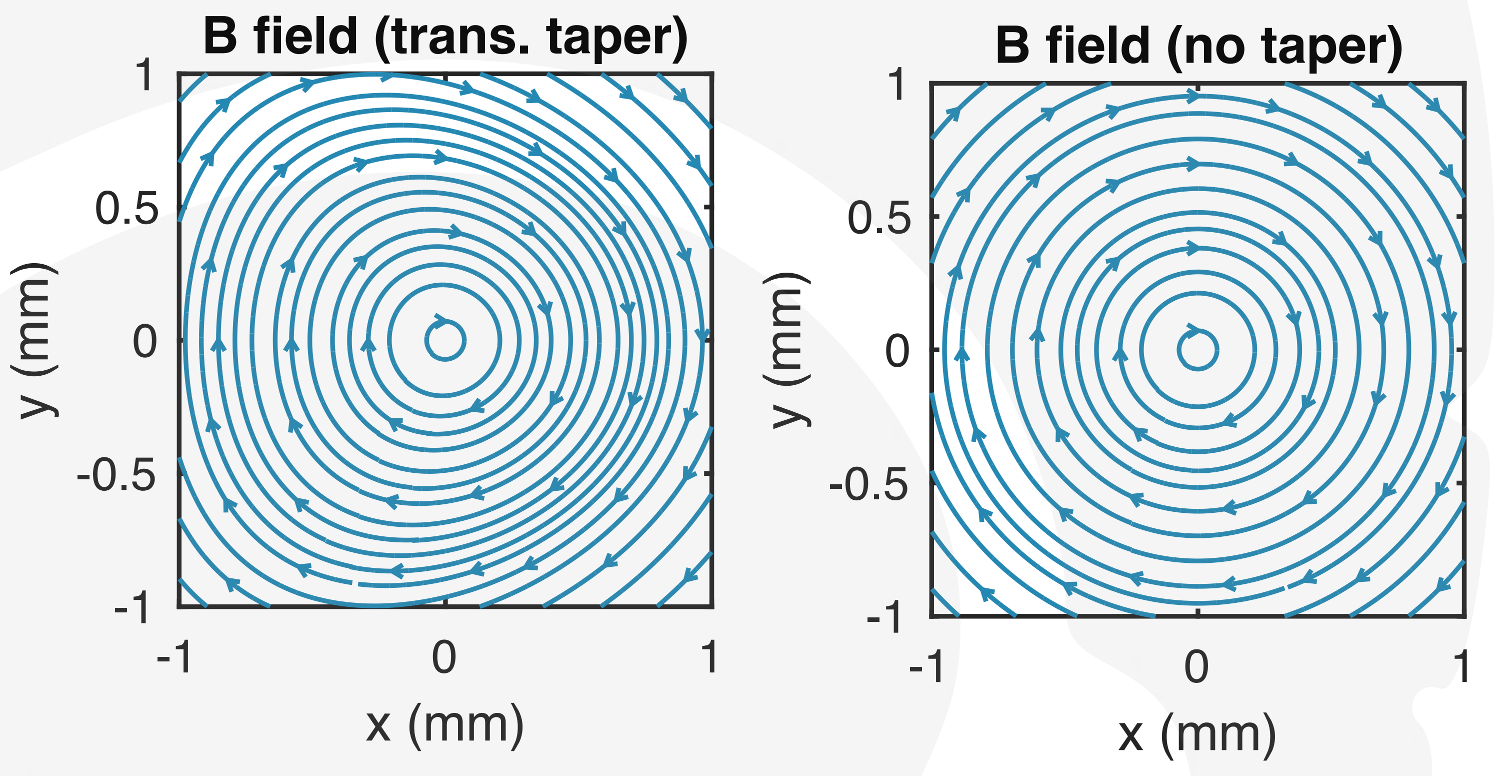


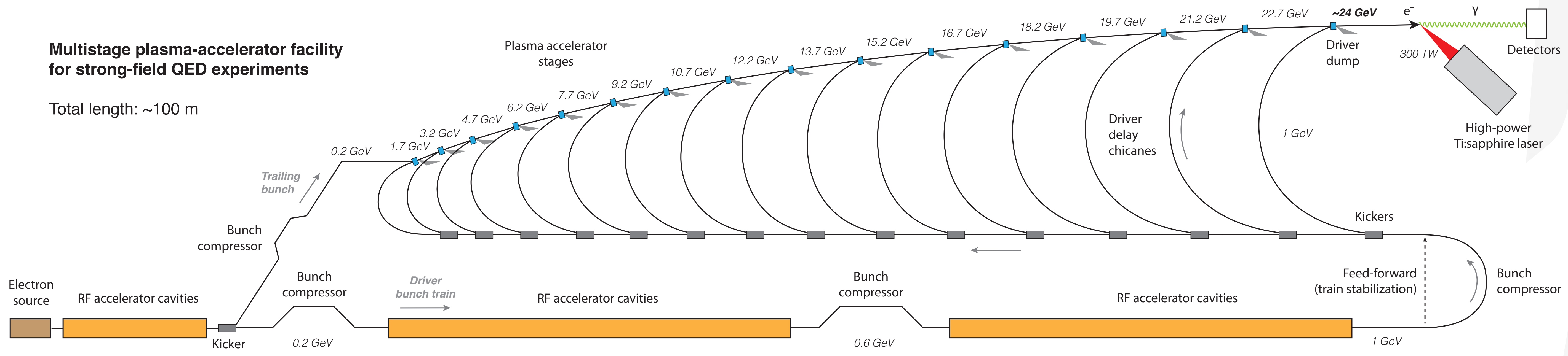
Source: Blackburn et al., Phys. Plasmas 25, 083108 (2018)

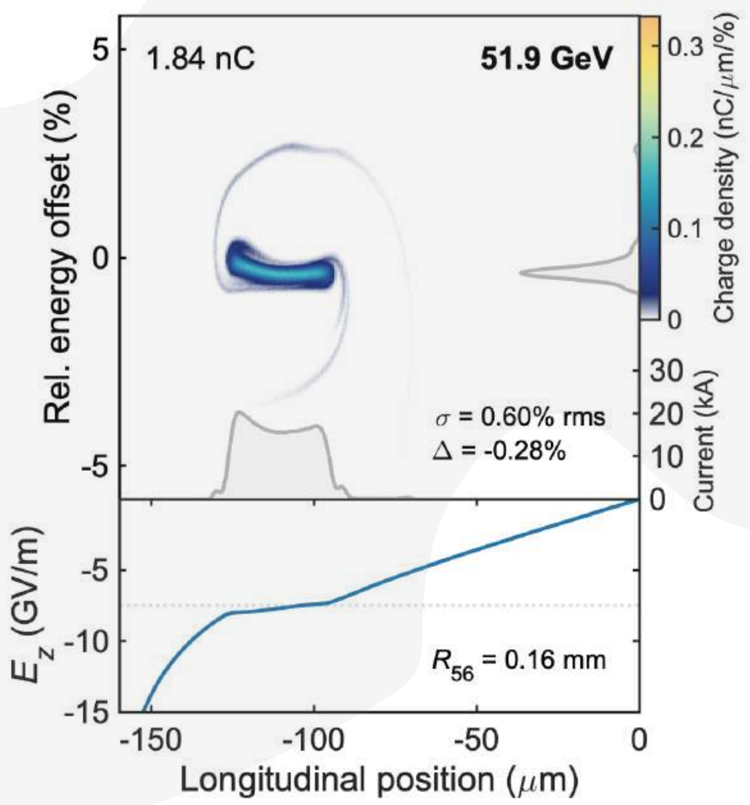
Stepping stone: **A near-term application to strong-field QED**

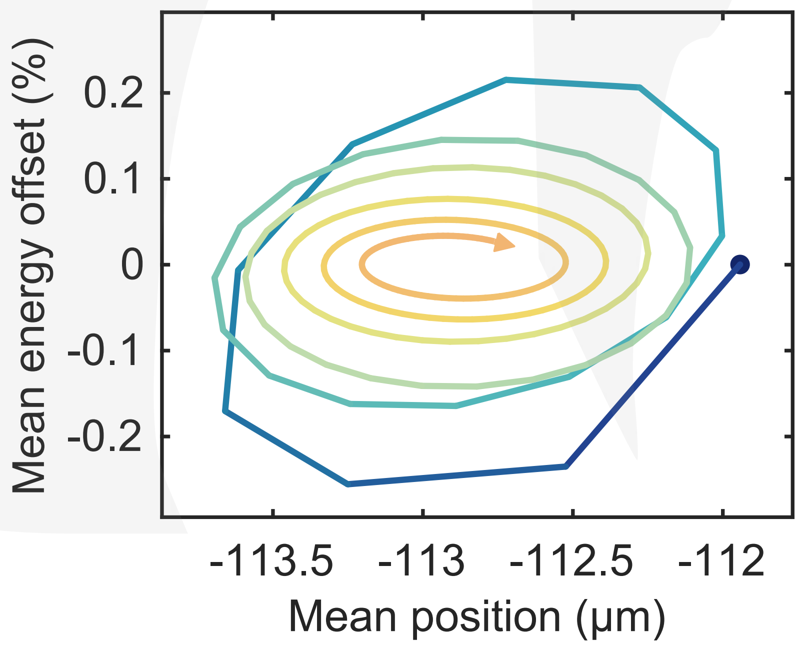
- Strong-field QED experiments require:
  - High energy (*staging*) and high stability (*self-correction*)
  - But not high rep. rate, power, beam quality or polarization.
- The SPARTA project will investigate and develop:
  1. Nonlinear plasma lenses — for achromatic staging
  2. Self-correction mechanisms — for passive stabilization
  3. Blueprints for a strong-field QED machine.

The SPARTA project
Staging of Plasma Accelerators for Realizing Timely Applications









Lindstrøm, arXiv:2104.14460

The SPARTA project

Staging of Plasma Accelerators
for Realizing Timely Applications

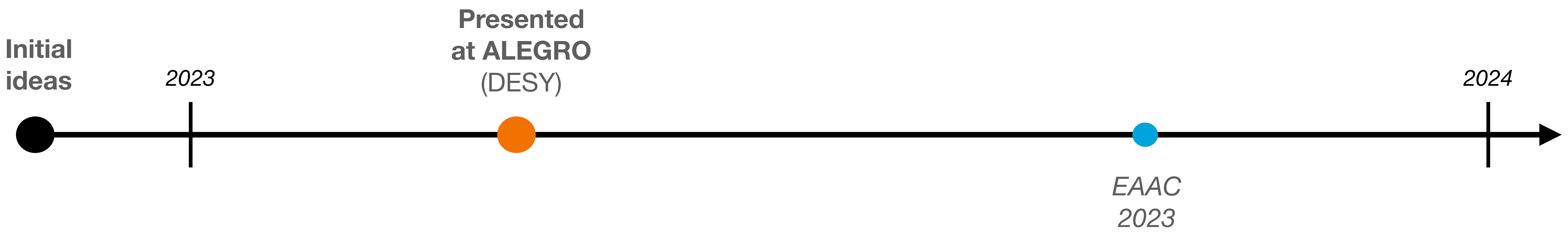
Currently recruiting postdocs and PhD students

(earliest start date Jan 2024)

Get in touch* if you are interested

* c.a.lindstrom@fys.uio.no

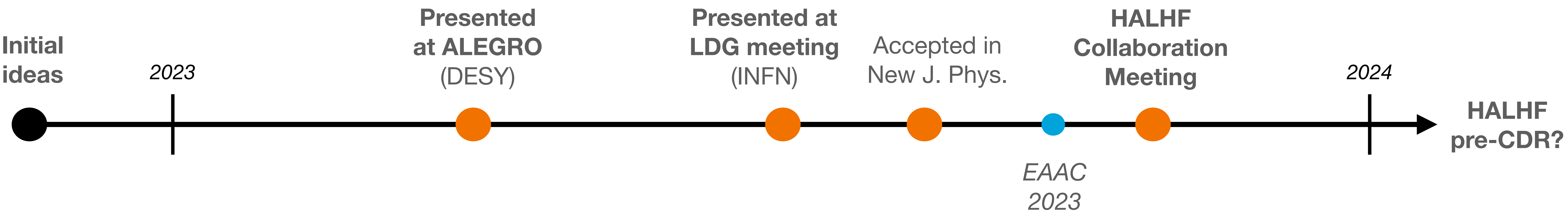
Current progress: **HALHF in 2023 and beyond**



> **Presented at ALEGRO workshop (22–24 March 2023)**
  — discussed as possible “flagship”
  — discussions on relation to wider plasma-accelerator research

Talk (Friday 11:30)
The plans to prepare for the next European Strategy
— Rajeev Pattathil (RAL)

Current progress: **HALHF in 2023 and beyond**

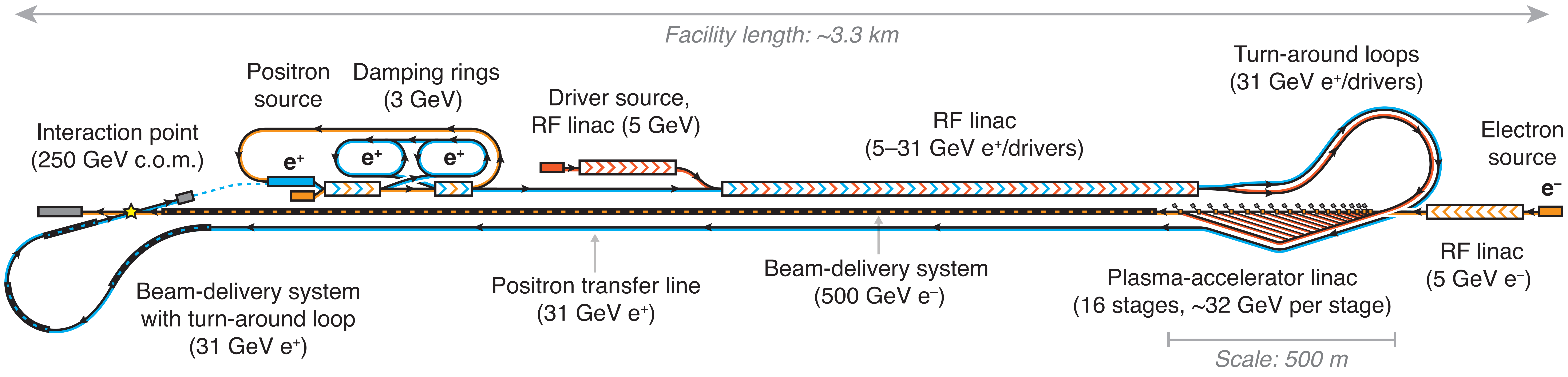


- **Presented at ALEGRO workshop (22–24 March 2023)**
  - — discussed as possible "flagship"
  - — discussions on relation to wider plasma-accelerator research
- **Presented at Lab Directors Group meeting (12–13 July 2023)**
  - — compared to muon collider, ERL collider, RF and magnet technology
  - — discussions about avenues for funding (e.g., CERN, STFC, etc.)
  - — discussions about collaboration with conventional collider experts (e.g., CLIC)
- **HALHF Collaboration Meeting (23 October 2023)**
  - — start interaction/interface between plasma + RF + detector research

Conclusion — HALHF

Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

- **The HALHF concept proposes a compact, cheaper, possibly quicker Higgs factory**
  - Asymmetric energy — asymmetric charge — asymmetric emittance
- **High risk/high reward: Less mature than RF, but cost is only "national-scale" (few $B)**
  - Near-term demonstrator crucial to building credibility — strong-field QED machine
- **Much targeted R&D still required (e.g., staging, beam quality, beam power)**
  - Currently assembling a collaboration with experts from plasma/RF/detectors



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PLEASE JOIN US!

HALHF Collaboration Meeting (23 Oct 2023)

HALHF project page:
https://jai.web.ox.ac.uk/node/3516526