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The HALHF concept:

A Hybrid, Asymmetric, Linear Higgs Factory

Combining the strengths of RF
and plasma-based accelerators

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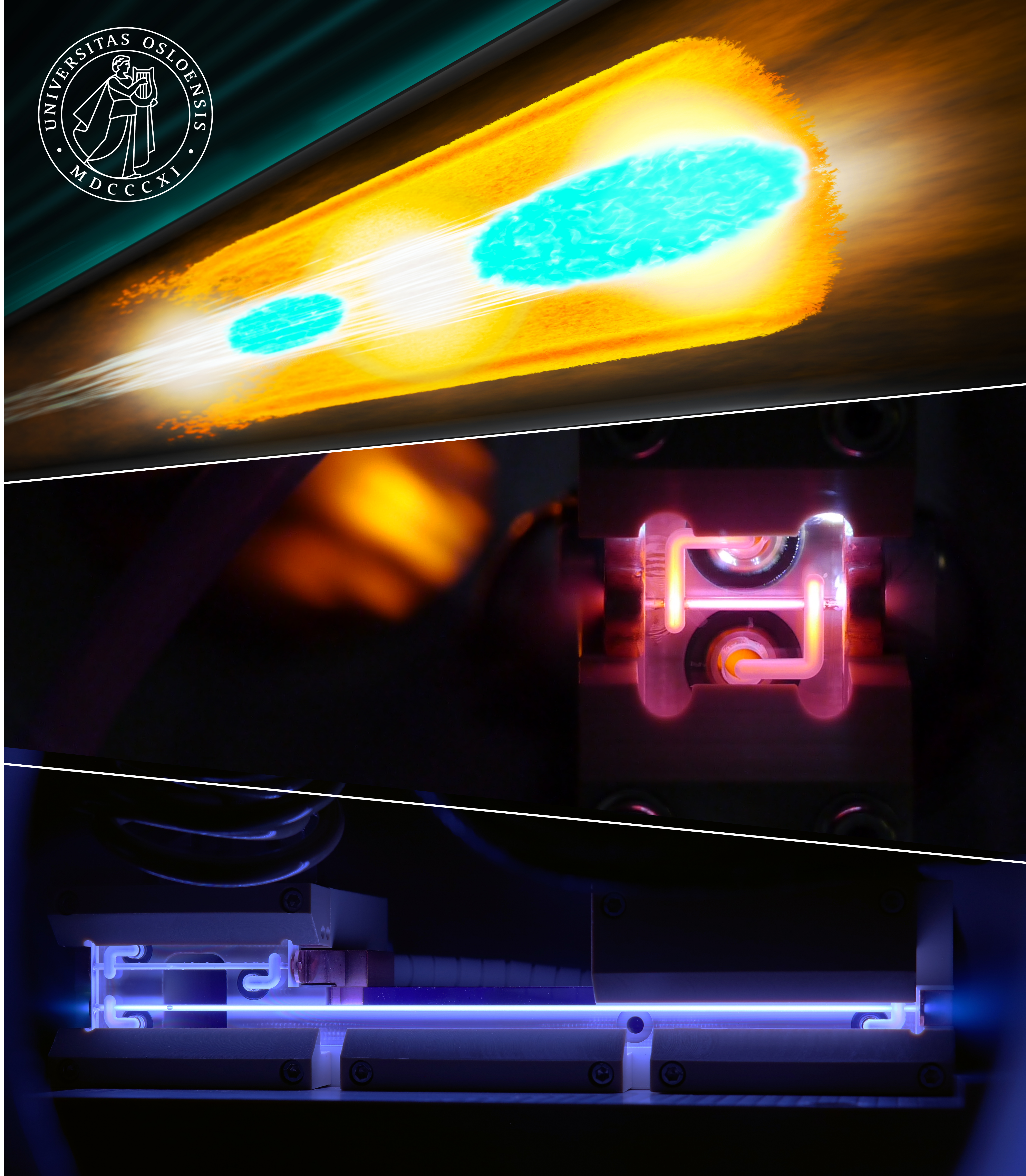

Toward a credible plasma-based e⁺e⁻ collider

- Several proposals over the past decades:
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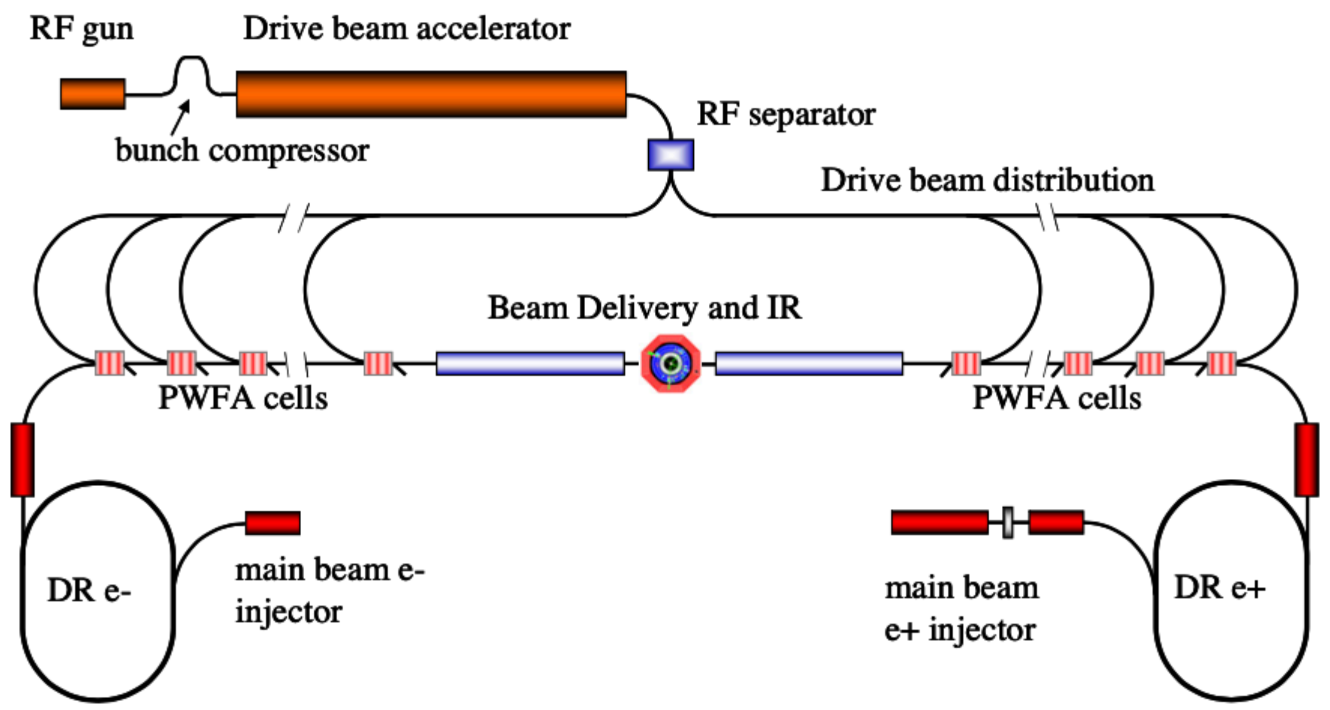
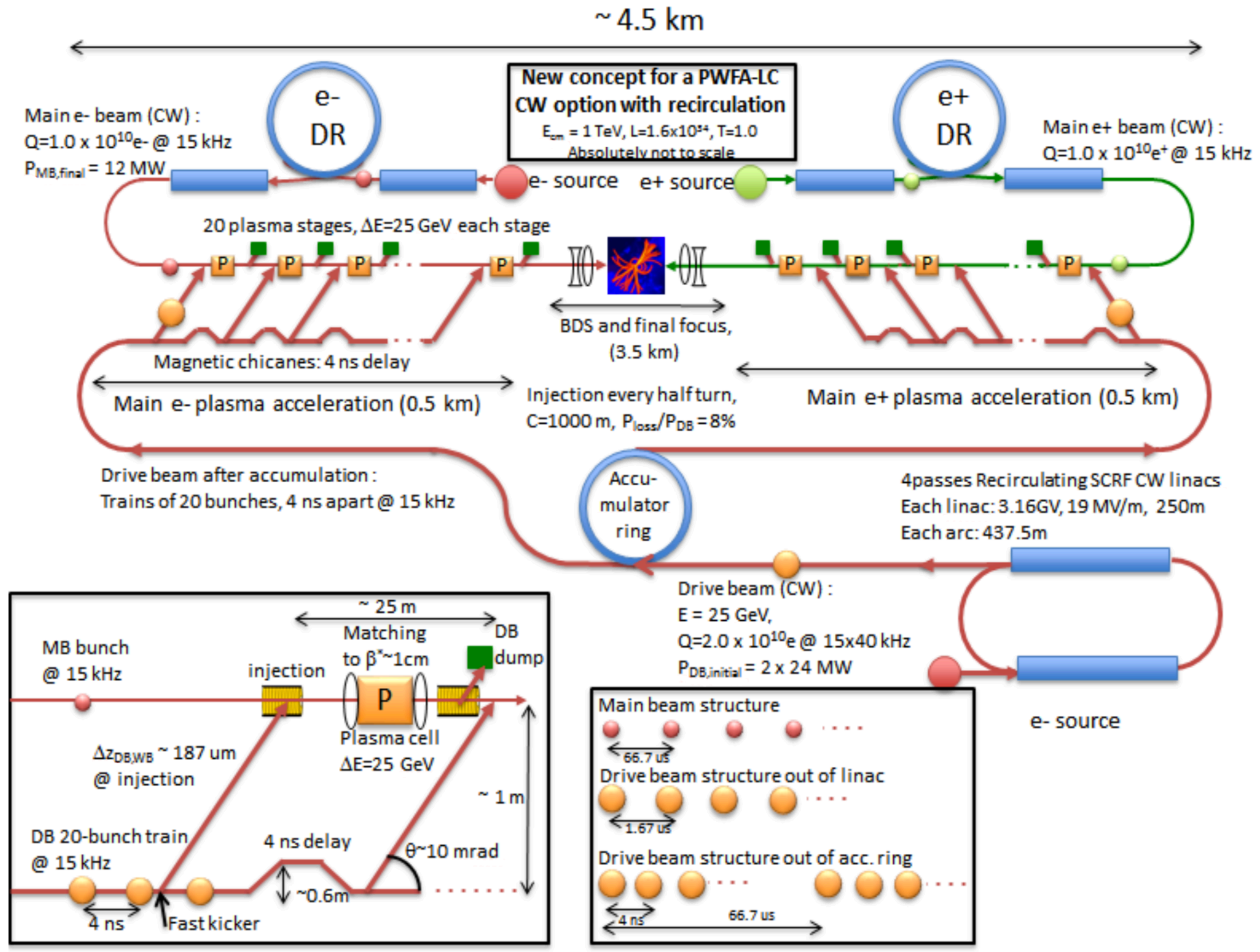


Source: Pei et al., Proc. PAC (2009)



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

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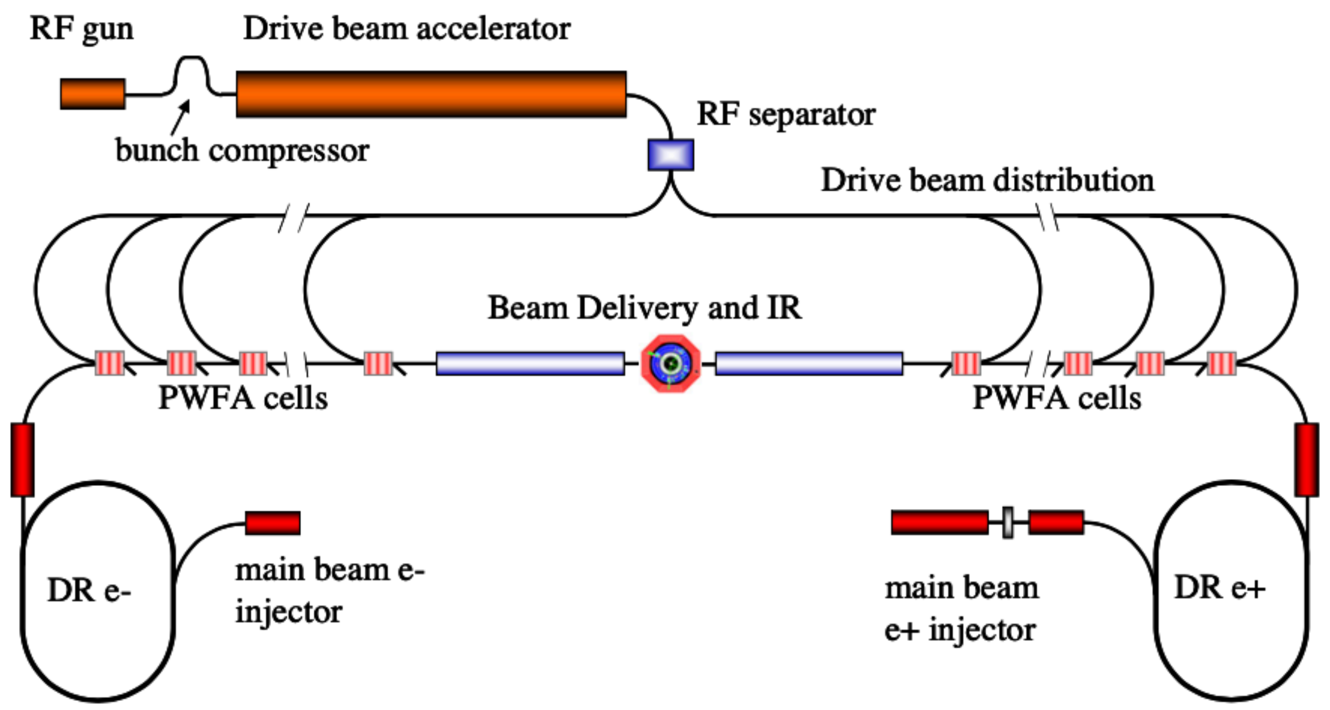
- **Very useful exercises to focus the R&D**
- Some key topics have been identified:
  - *Positron acceleration*
  - *Energy efficiency*



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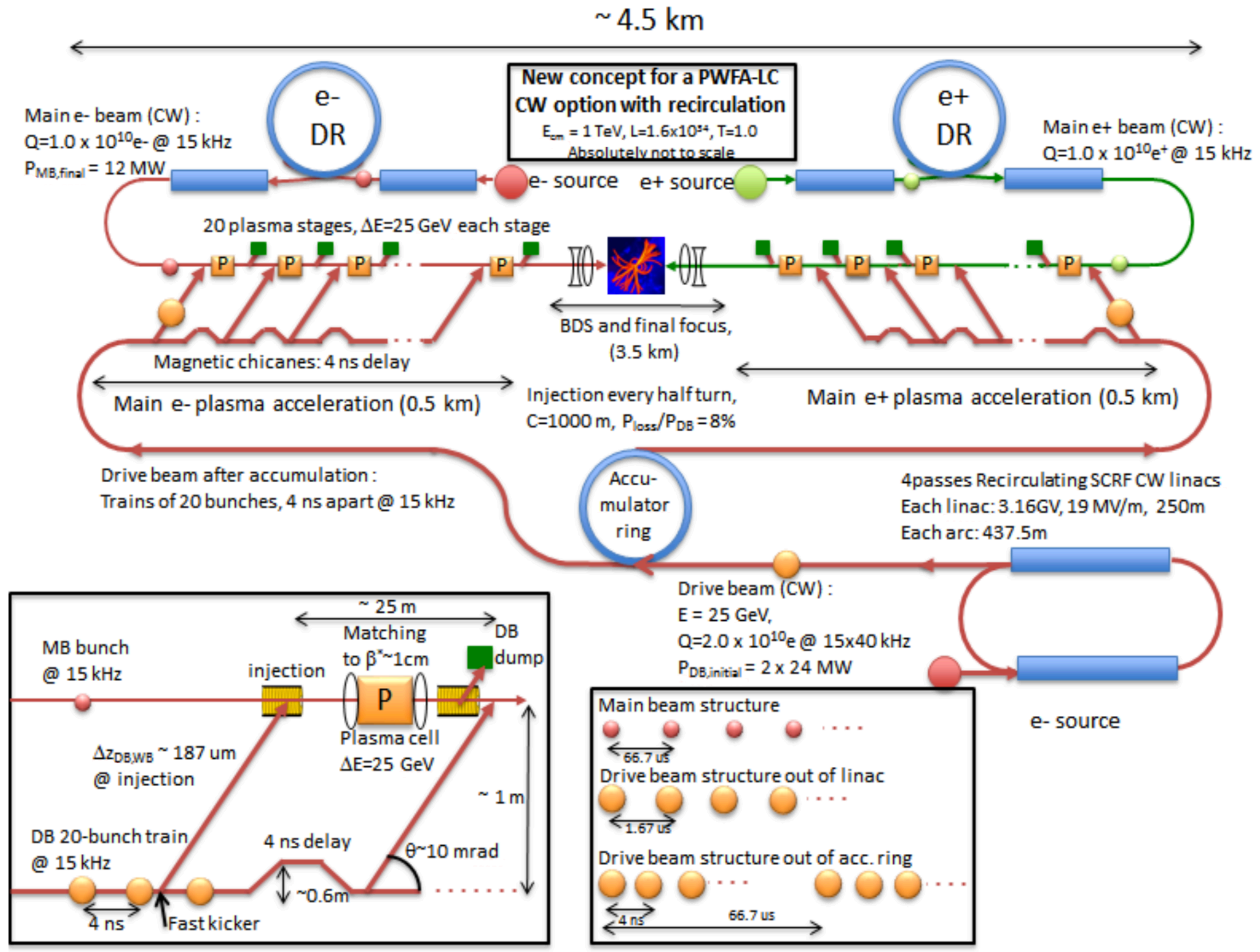

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The HALHF strategy: **Design based on current constraints**

- Design decision #1: **only accelerate electrons in plasma (and positrons using RF)**
  - Plasmas are charge asymmetric → e^- acceleration does not imply e^+ acceleration.
  - e^+ acceleration schemes exist, but are not currently both efficient and quality-preserving.

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  - CLIC demonstrates that electrons can be produced efficiently.
  - PWFA experiments have shown high energy-transfer efficiency.

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- **The basis of these decisions could change in the near future (with continued R&D):**
  - Promising ideas for positron acceleration (Diederichs *et al.* +++)
  - Promising developments toward high-efficiency lasers: fibre-lasers, BAT, etc.

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): $$\gamma = \frac{1}{2}\left(\frac{2E_p}{\sqrt{s}} + \frac{\sqrt{s}}{2E_p}\right)$$

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$$\gamma = \frac{1}{2}\left(\frac{2E_p}{\sqrt{s}} + \frac{\sqrt{s}}{2E_p}\right)$$

- A reasonable choice is:
  - Electrons (from PWFA): **E_e = 500 GeV** (4 times higher)
  - Positrons (from RF accelerator): **E_p = 31 GeV** (4 times lower)
  - Boost: **γ = 2.13**
    (HERA had a boost of γ ≈ 3)

Simulating asymmetric e+/e− collisions

- GUINEA-PIG beam–beam simulations:
  - **Asymmetric energies give similar luminosity**
  - However, **more power is required** (to boost the collision products)

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 match for smaller IP beta functions)

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: $$\frac{P}{P_0} = \frac{N_e E_e + N_p E_p}{N\sqrt{s}}$$

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- **Unchanged power usage if $N_e/N_p = E_p/E_e$** (in our case: 4x more e^+, 4x less e^-)
  - However, producing positrons is problematic—instead go for **2 times more e^+**

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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 inversely with energy.

> To achieve same beam size at IP:

> > **Positrons (lower energy) must have smaller IP beta function**:
> > use 3.3/0.1 mm (similar to CLIC)

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

- Geometric emittance scales inversely with energy.
- To achieve same beam size at IP:
  - **Positrons (lower energy) must have smaller IP beta function**:
    use 3.3/0.1 mm (similar to CLIC)
  - However, electrons can have a larger IP beta function
    - **More interestingly, we can increase the e⁻ (normalised) emittance.**
    - Significantly reduces emittance requirements from PWFAs!

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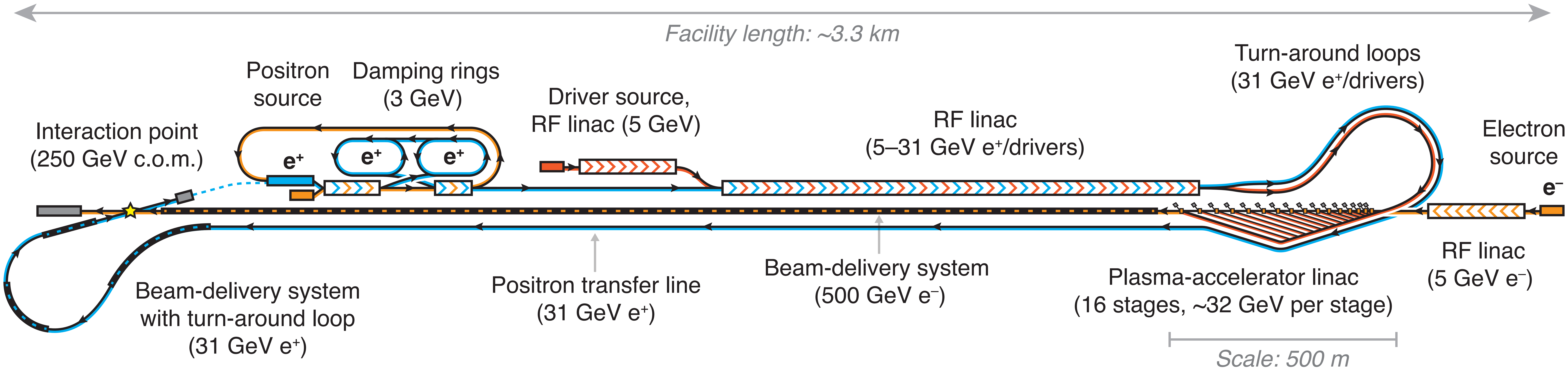
31.3 / 500	75 / 75	4 / 1	10 / 80	35 / 280	3.3 / 6.5	0.10 / 0.20	0.94	0.54	1.25
31.3 / 500	75 / 75	4 / 1	10 / 160	35 / 560	3.3 / 3.3	0.10 / 0.10	0.81	0.46	1.25

Schematic layout of HALHF



Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

- Overall length: ~3.3 km ⇒ **fits in ~any major particle-physics lab**
  - Length dominated by e^- beam-delivery system

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 (“total project cost”): **$2.3–3.9B**

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%

- Dominated by conventional collider costs (97%) — **PWFA linac only ~3% of the cost**

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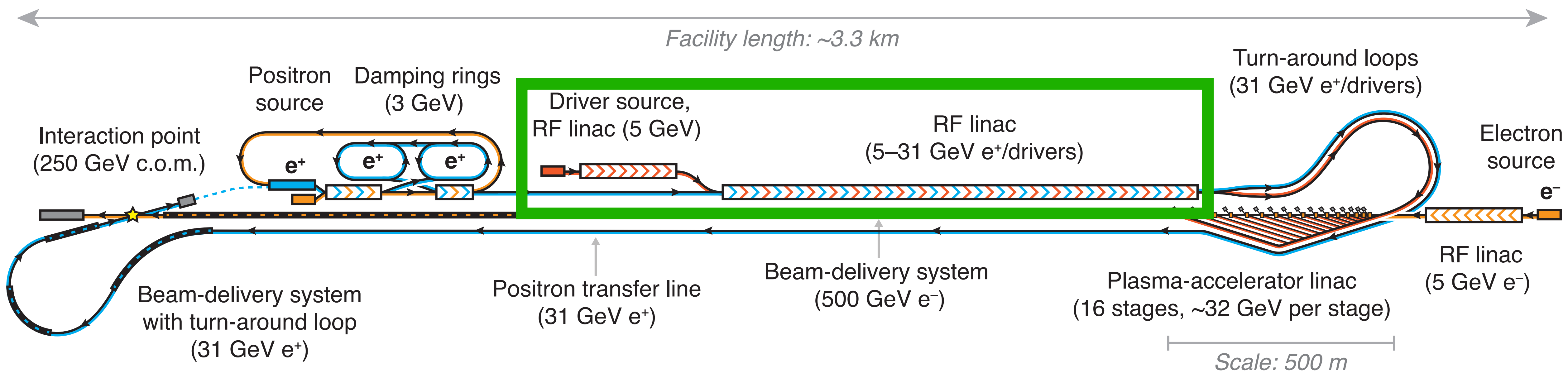
- Dominated by conventional collider costs (97%) — **PWFA linac only ~3% of the cost**
- Estimated **power usage is ~100 MW** (similar to same-energy ILC and CLIC):
  - *21 MW beam power + 27 MW power loss + 2 x 10 MW damping rings + 50% facility overhead*

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

- Length = ~1.3 km / gradient = 25 MV/m
- Assumes 50% efficient acceleration

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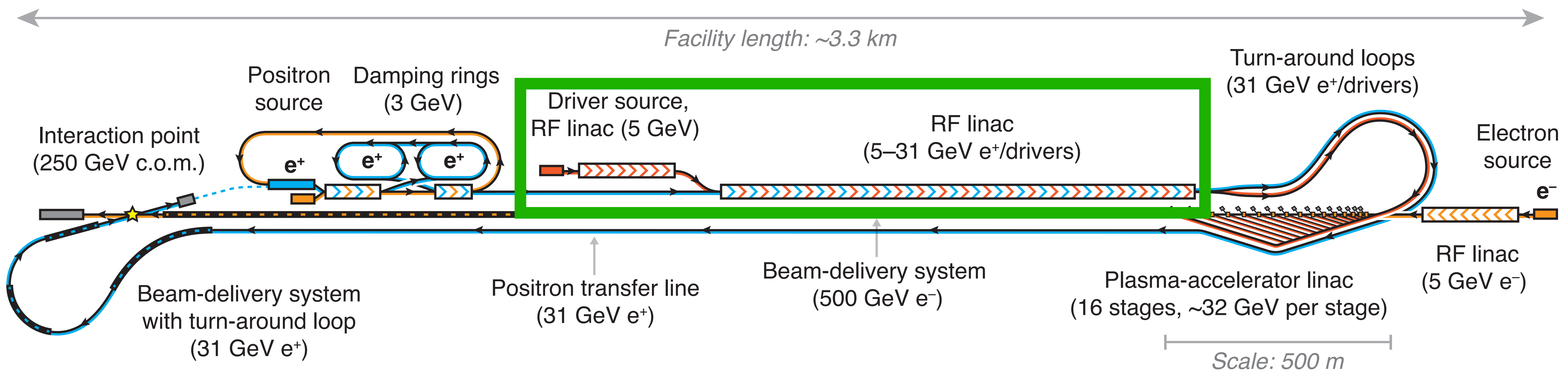

- Length = ~1.3 km / gradient = 25 MV/m
- Assumes 50% efficient acceleration
- Bunch-train pattern must be compatible with PWFA (both NCRF/SCRF possible):
  - *Burst-mode (100 bunch-train at 100 Hz)*
  - *Continuous wave (10 kHz)*

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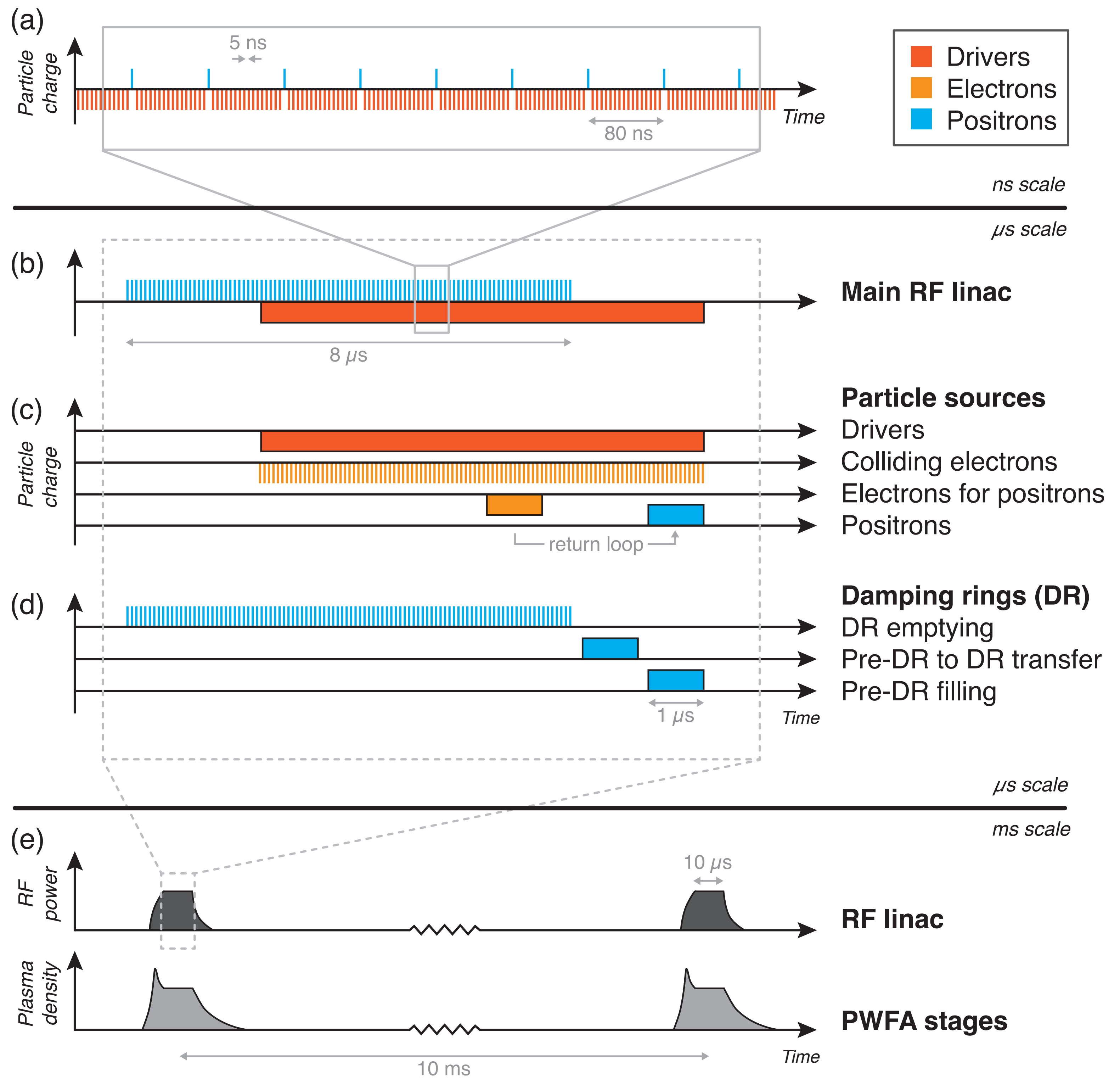
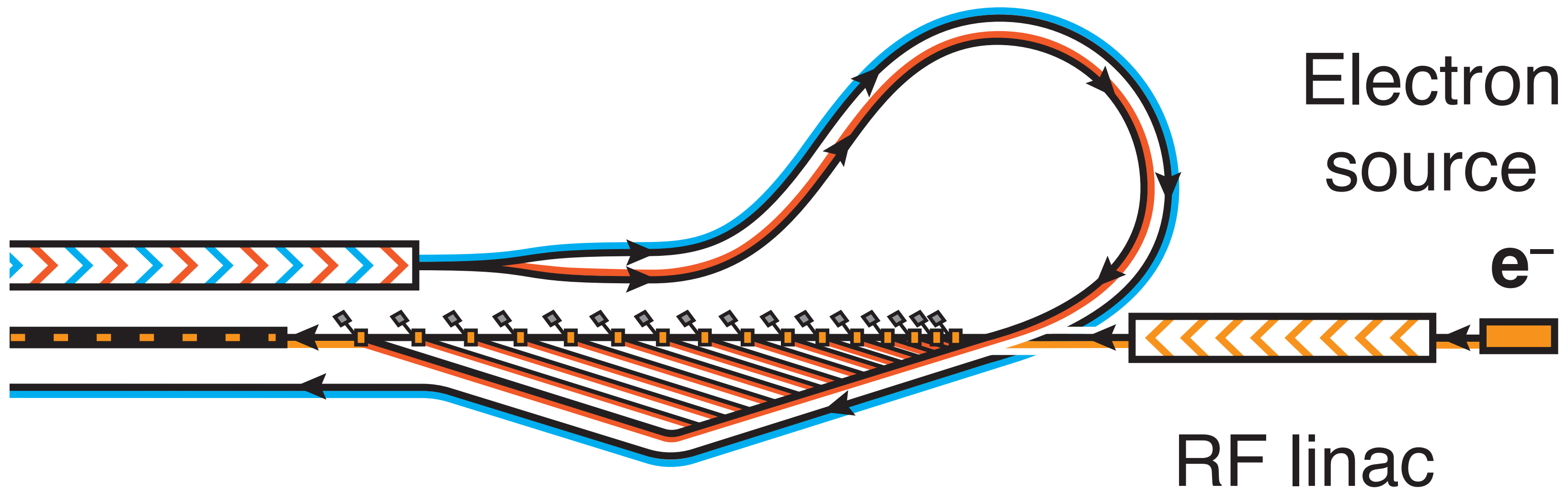


Possible bunch-train pattern for HALHF.

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

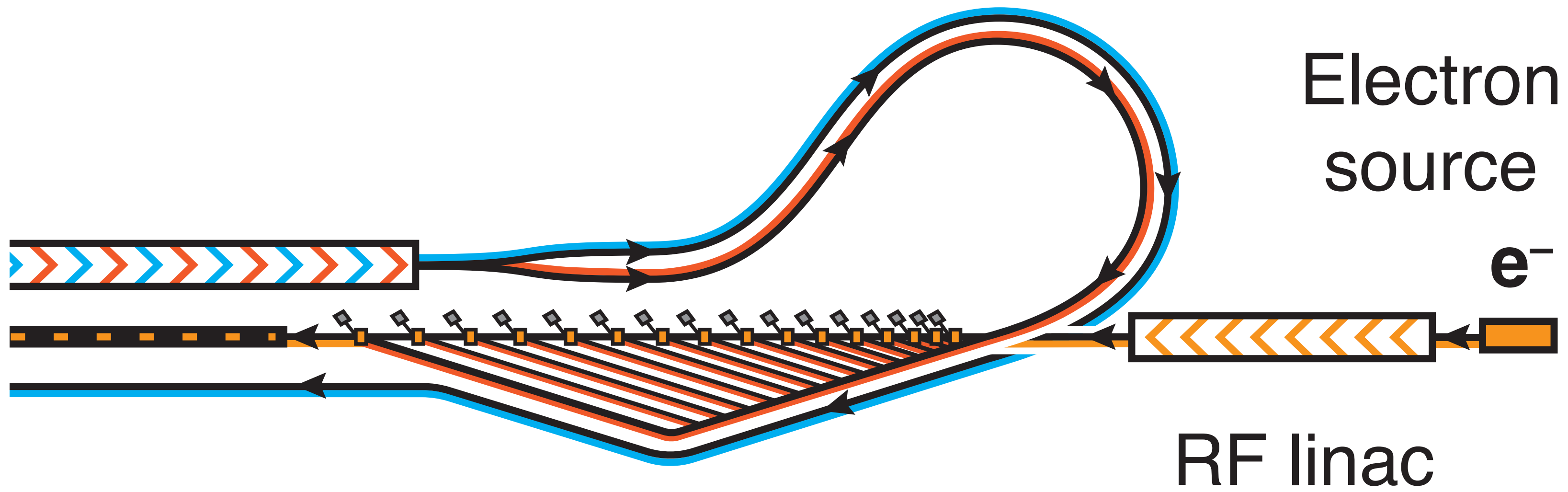
> No damping ring required (due to high-emittance electrons)

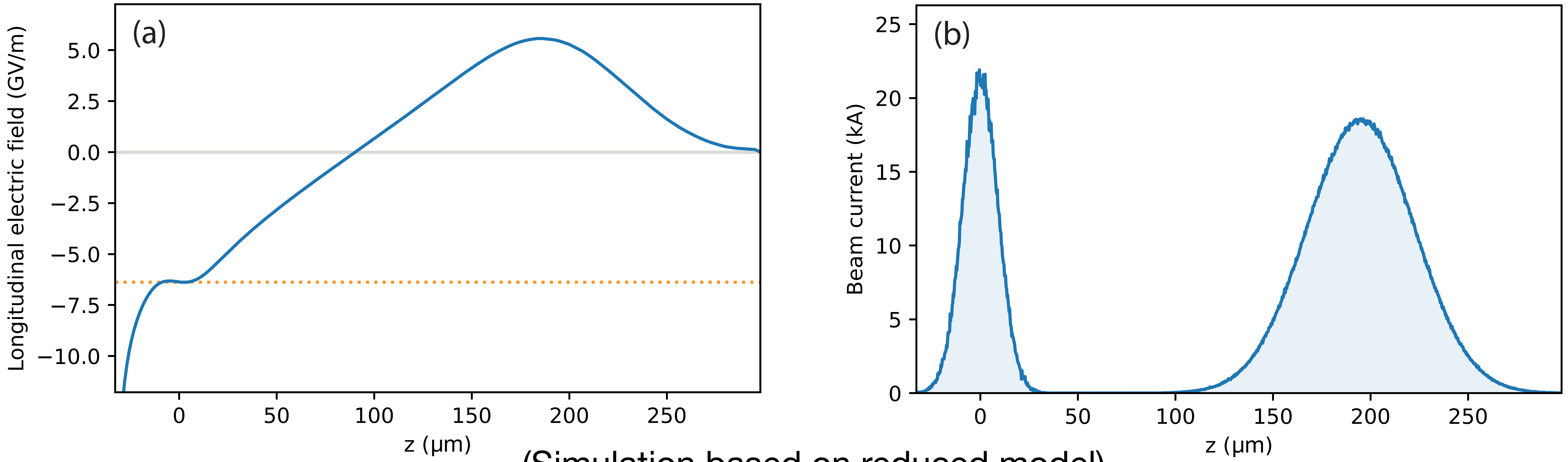


PWFA linac parameters		
Number of stages		16
Plasma density	cm^{-3}	1.5×10^{16}
In-plasma acceleration gradient	GV/m	6.4
Average gradient (incl. optics)	GV/m	1.2
Length per stage[a]	m	5
Energy gain per stage[a]	GeV	31.9
Initial injection energy	GeV	5
Driver energy	GeV	31.25
Driver bunch population	10^{10}	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

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

- No damping ring required (due to high-emittance electrons)
- 16 PWFA stages (each 5 m long)
  - *Length: ~400 m total (80 m of plasma)*
  - *Gradient: 6.4 GV/m (in plasma) / 1.2 GV/m (average)*
  - *Energy efficiency: 39%*
    (74% driver-to-plasma, 53% plasma-to-beam)





(Simulation based on reduced model)

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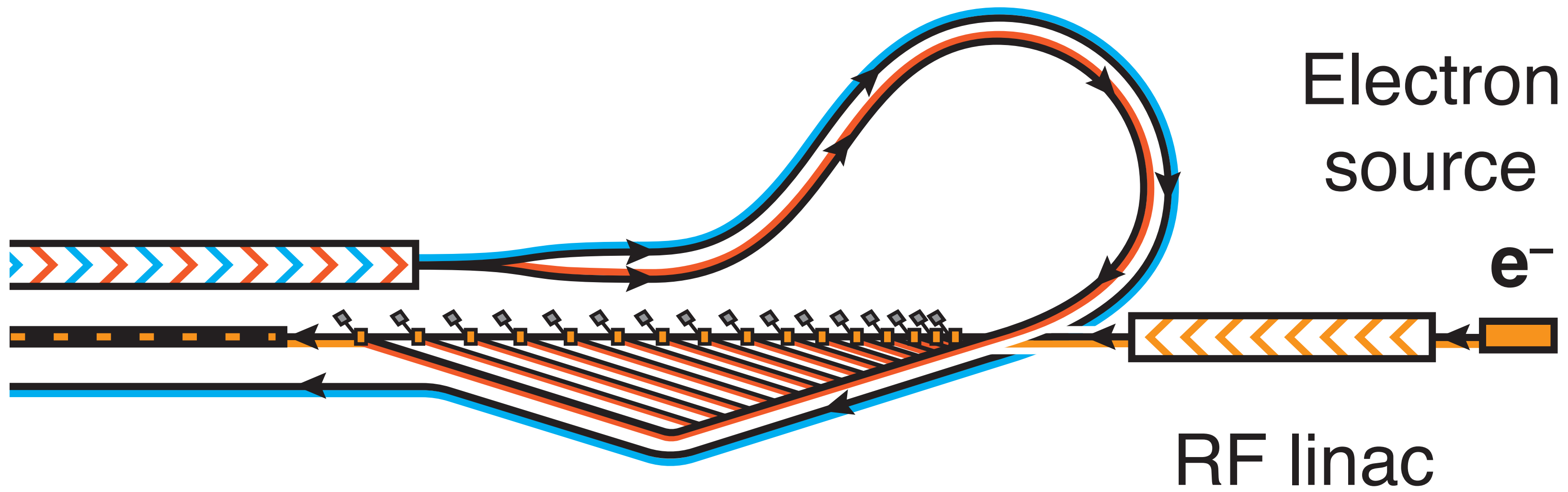

Key R&D topic:
Energy-efficiency vs. instability

Several promising mitigation strategies exist
(ion motion, quasi-linear regime, etc.)

More detailed study required to determine stable and
self-consistent parameters → **pre-CDR**

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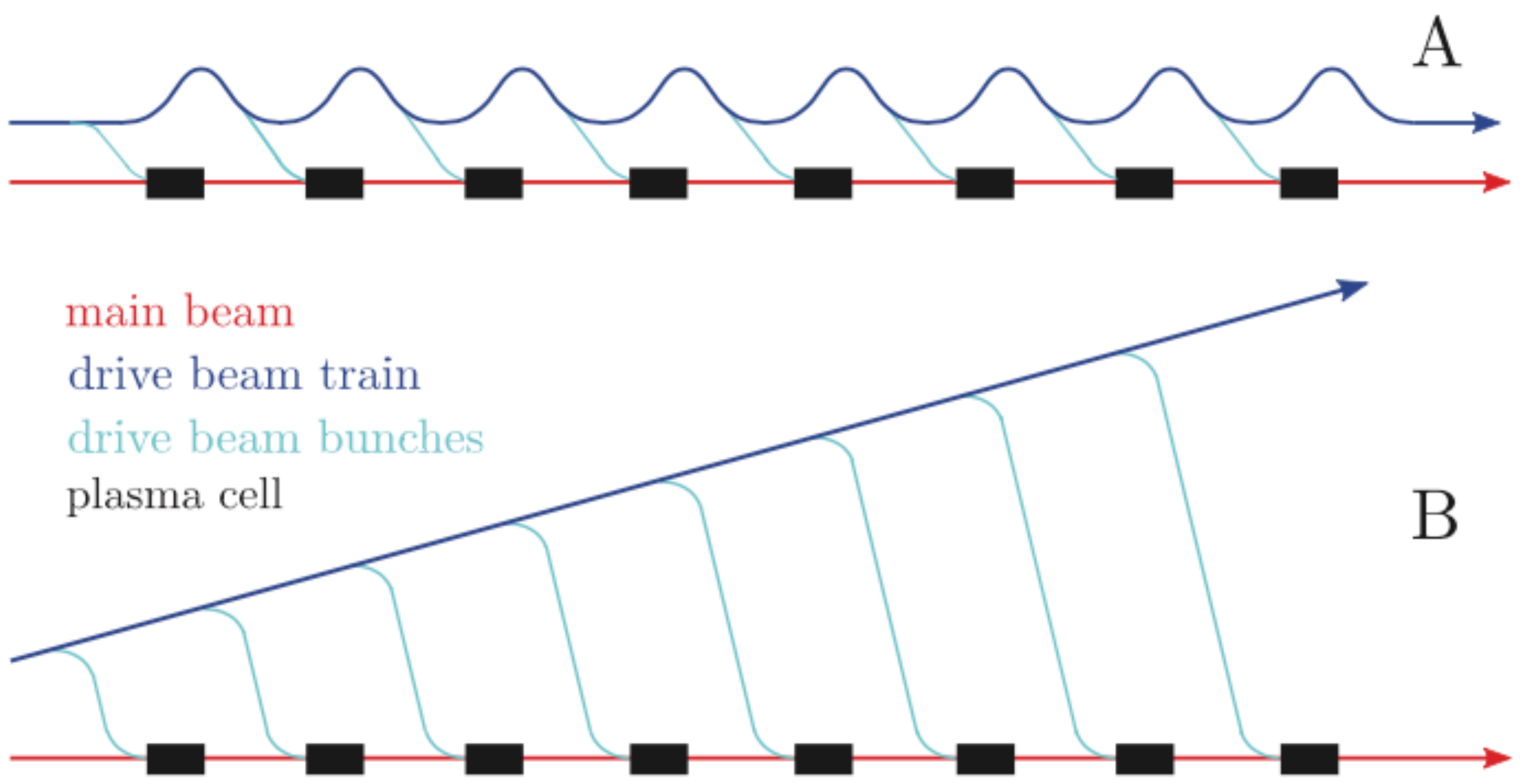
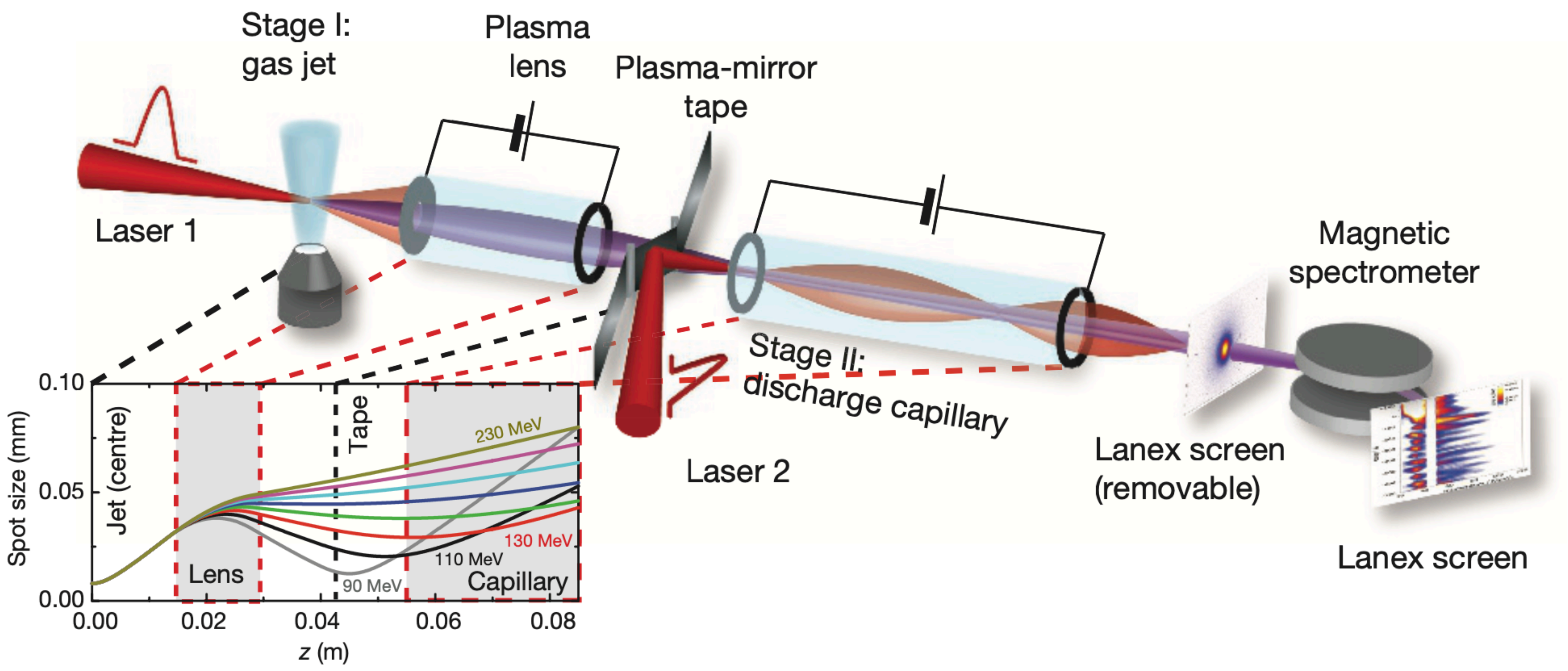
Innovations required: **Plasma-accelerator R&D**

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



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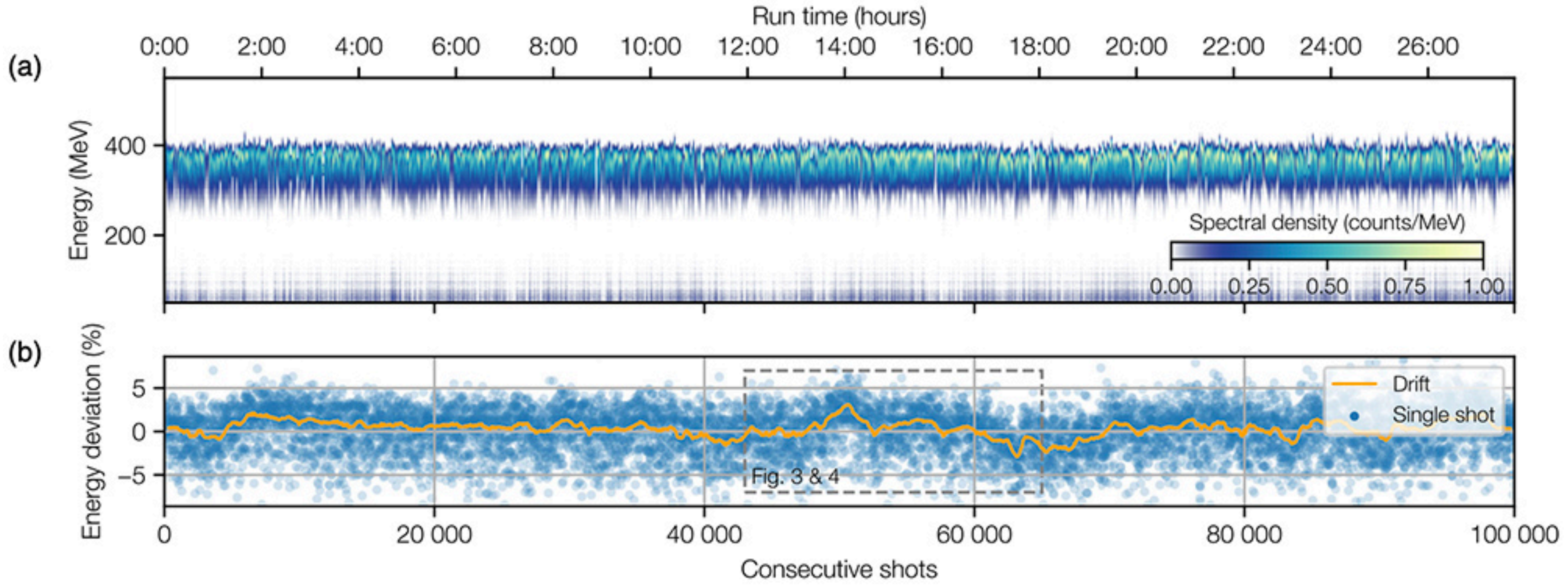
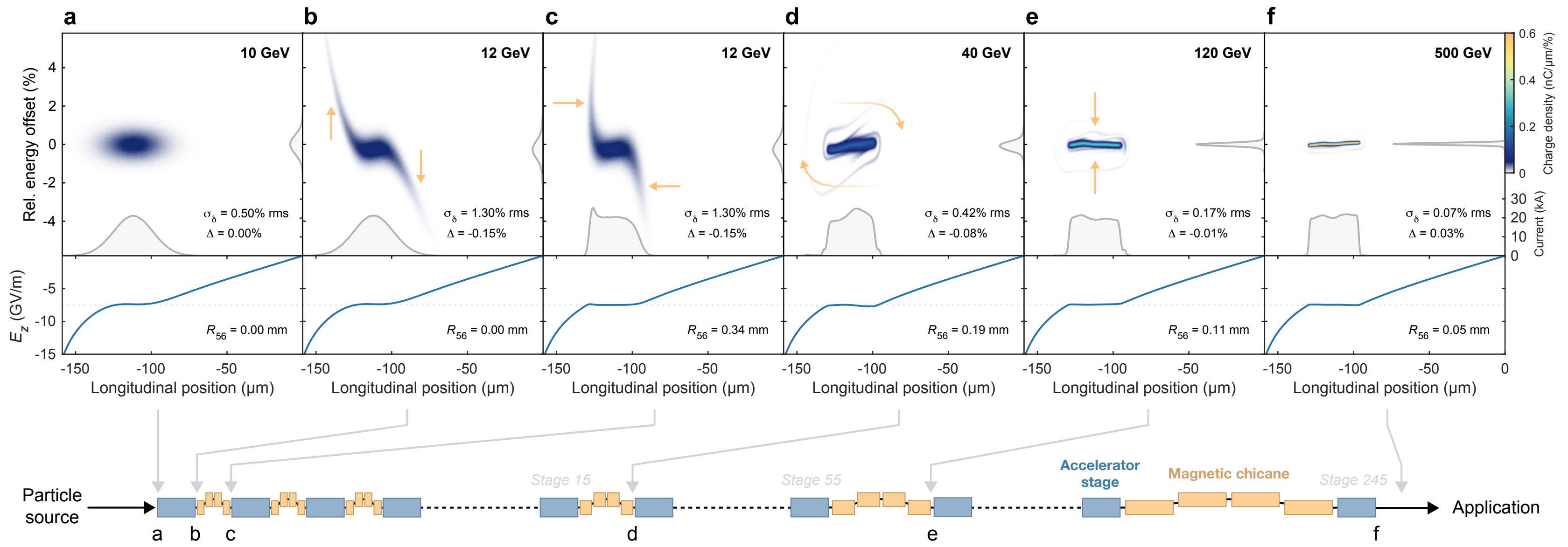
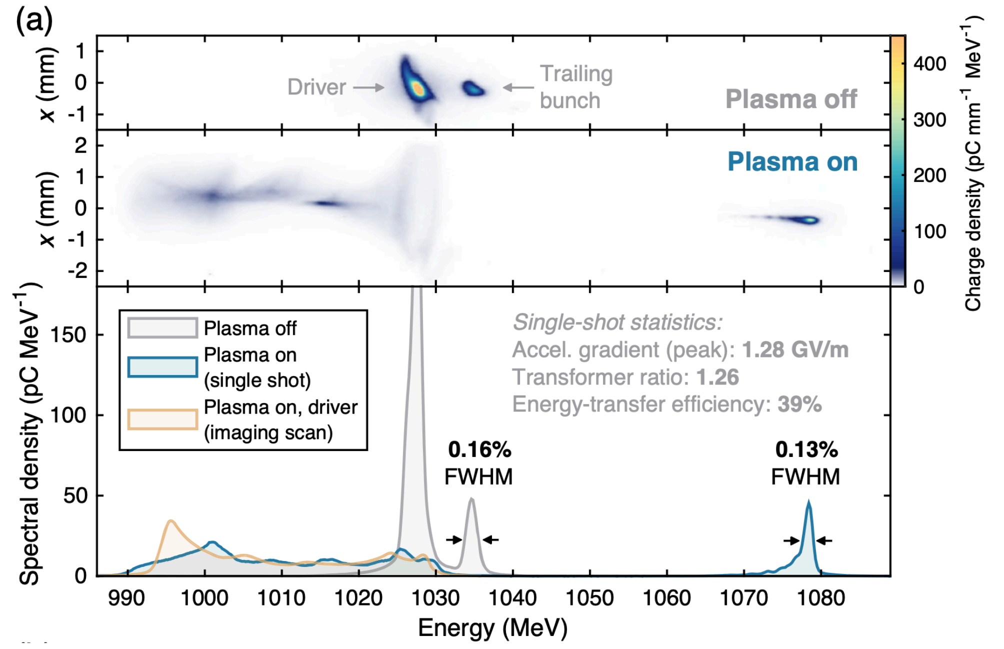
  - Multi-stage driver distribution
- Toward high beam quality:
  - Transverse and longitudinal stability
  - Emittance and energy-spread preservation
  - Spin-polarization preservation



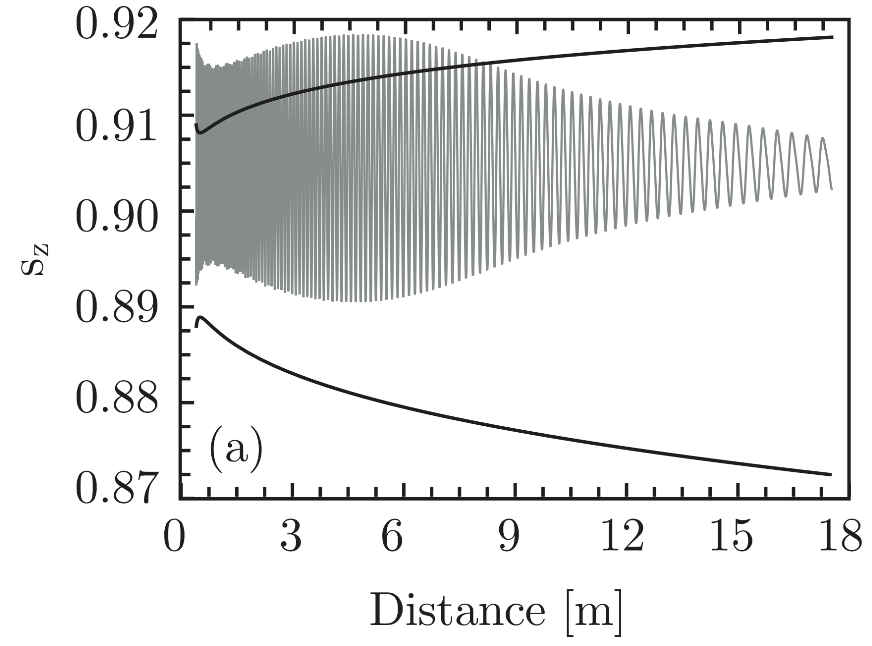
From: Maier et al., Phys. Rev. X 10, 031039 (2020).



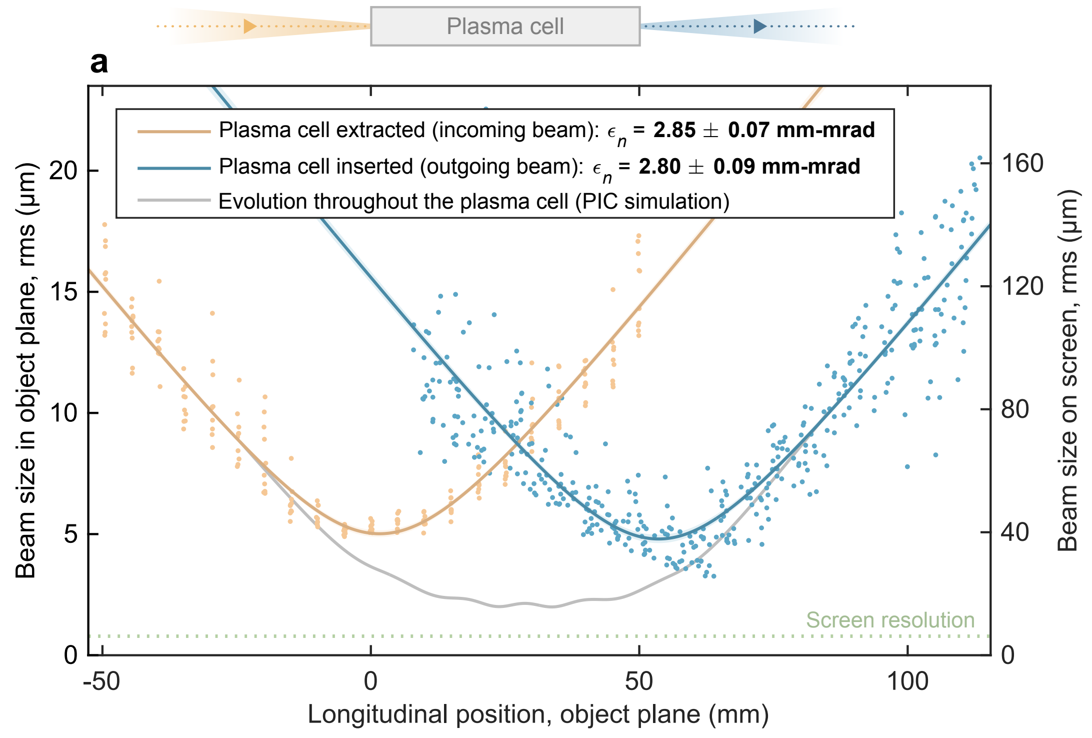
From: Lindstrøm (arXiv: 2104.14460).



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



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



From: Lindstrøm et al. (submitted)

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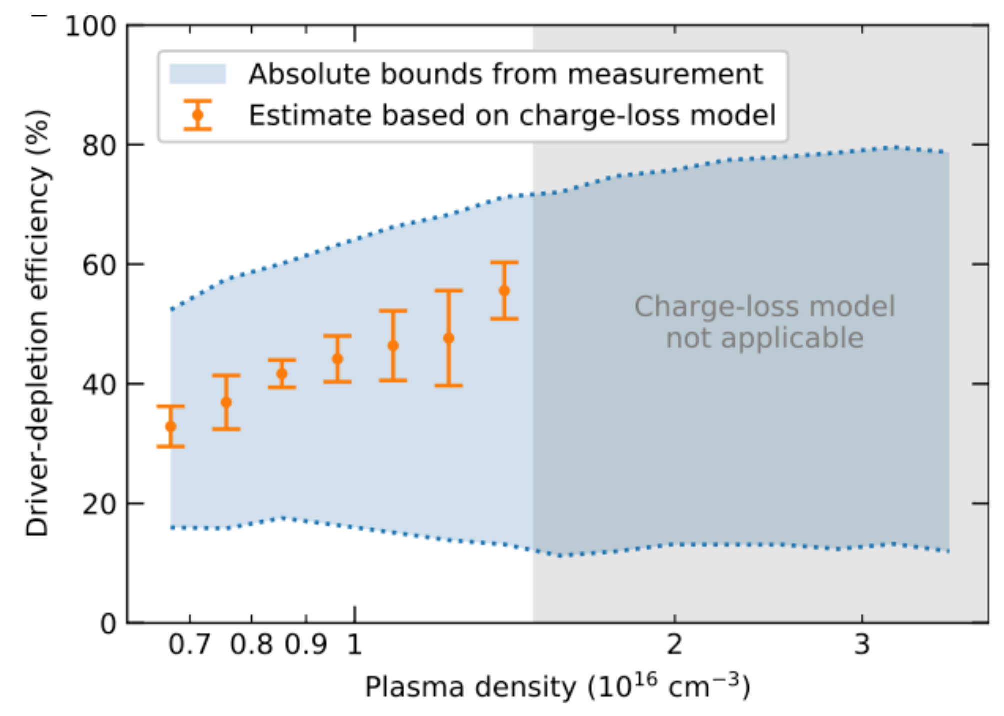
- Toward high beam quality:
  - Transverse and longitudinal stability
  - Emittance and energy-spread preservation
  - Spin-polarization preservation
- Toward high beam power:
  - High-overall efficiency (wall-plug to beam)
  - Repetition rate
  - Plasma-cell cooling

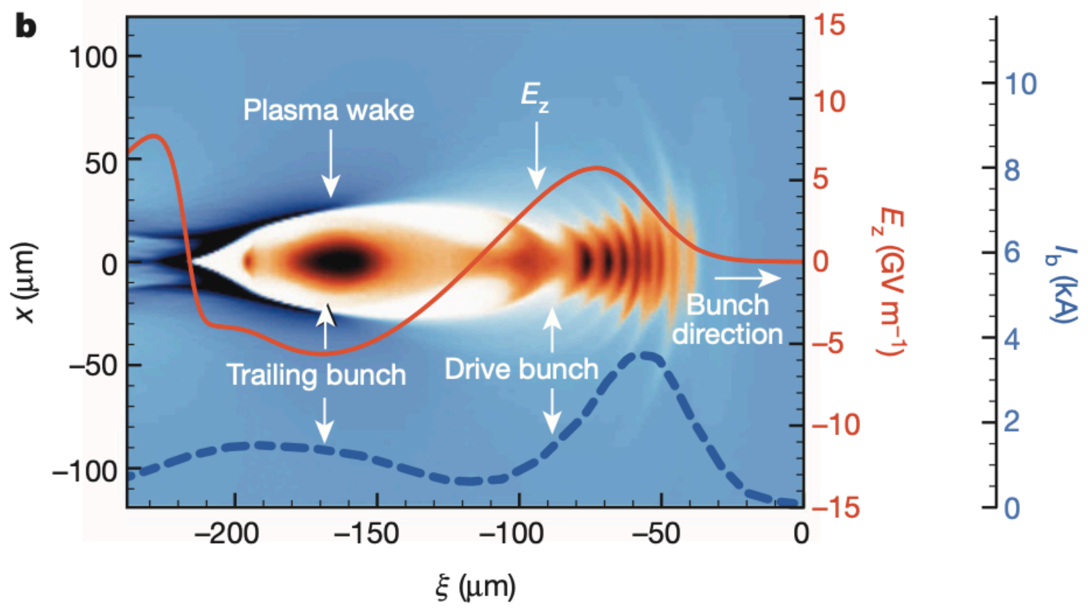
Depletion efficiency



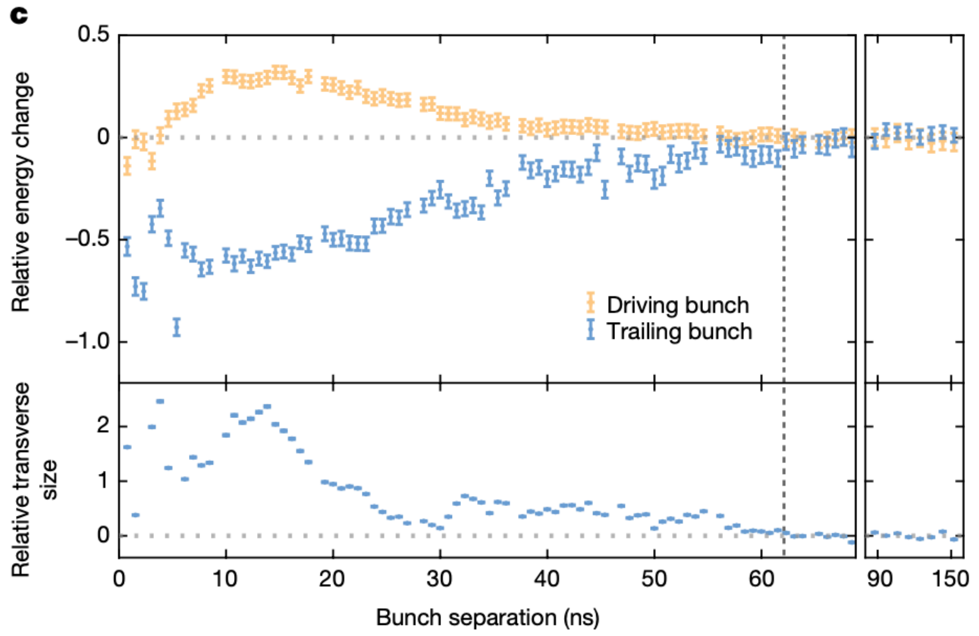
From: Peña et al. (arXiv:2305.09581)

(Must be achieved simultaneously)

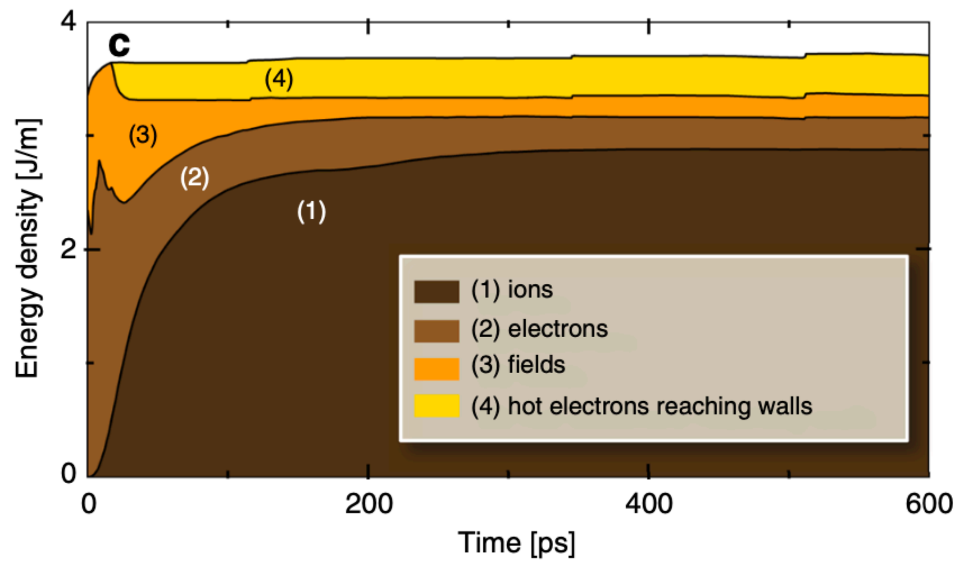
Extraction efficiency



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



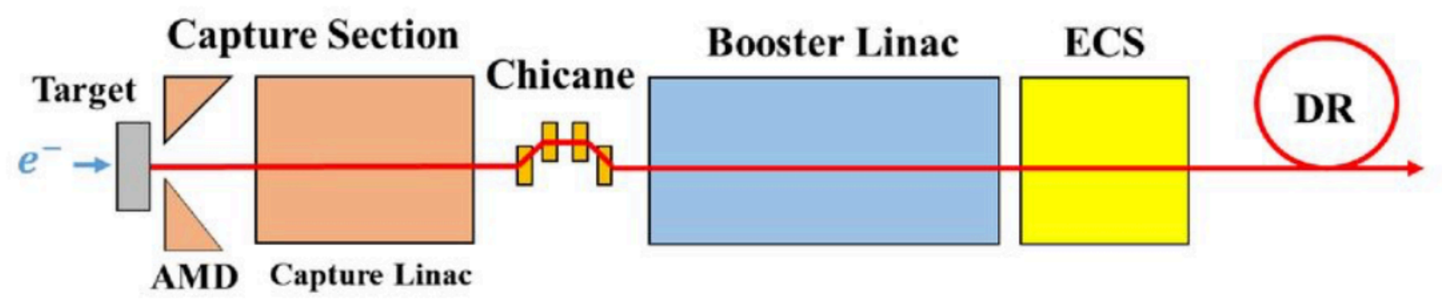
From: D'Arcy et al., Nature 603, 58 (2022).



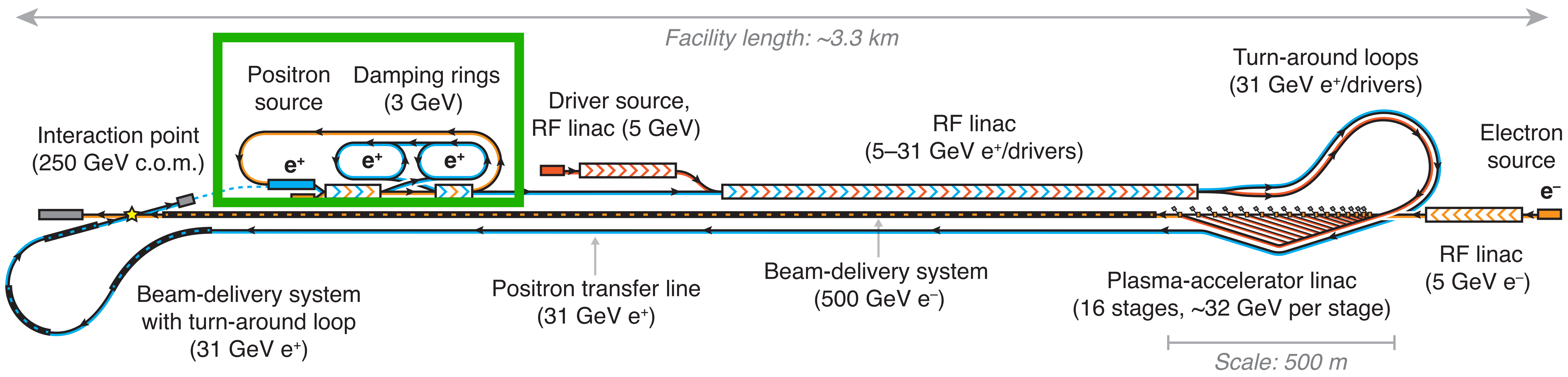
From: Zgadzaj et al.,
Nat. Commun. 11, 4753 (2020)

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

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



Sketch of ILC positron source



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

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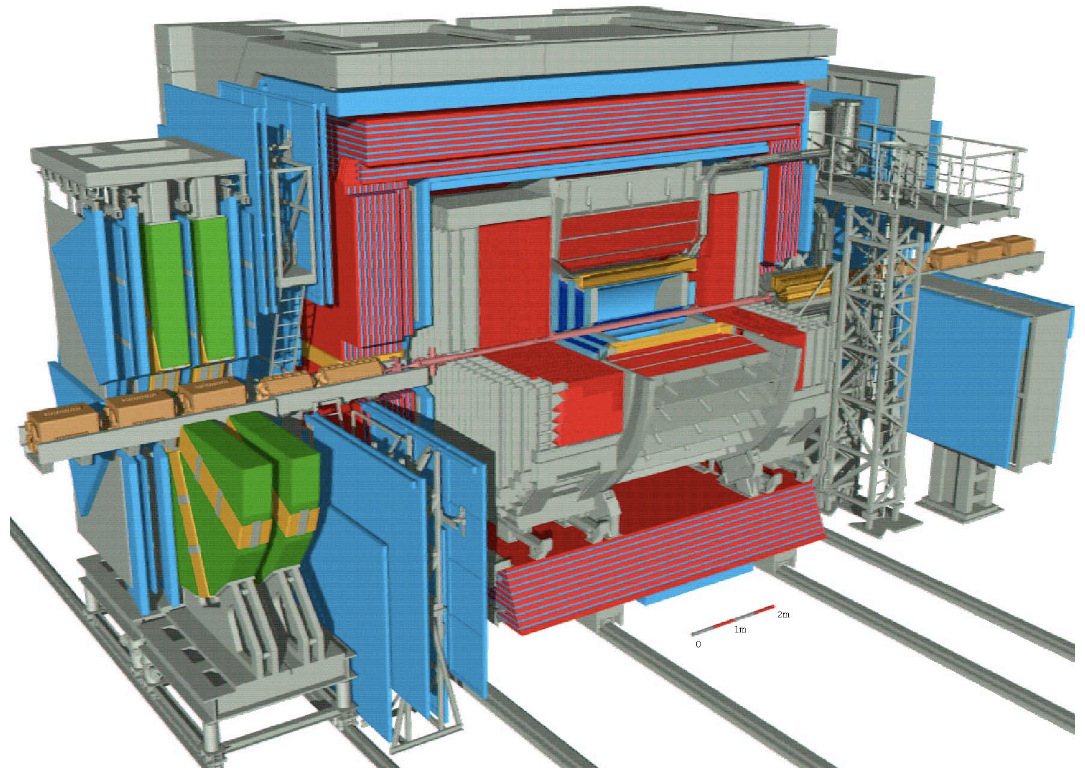
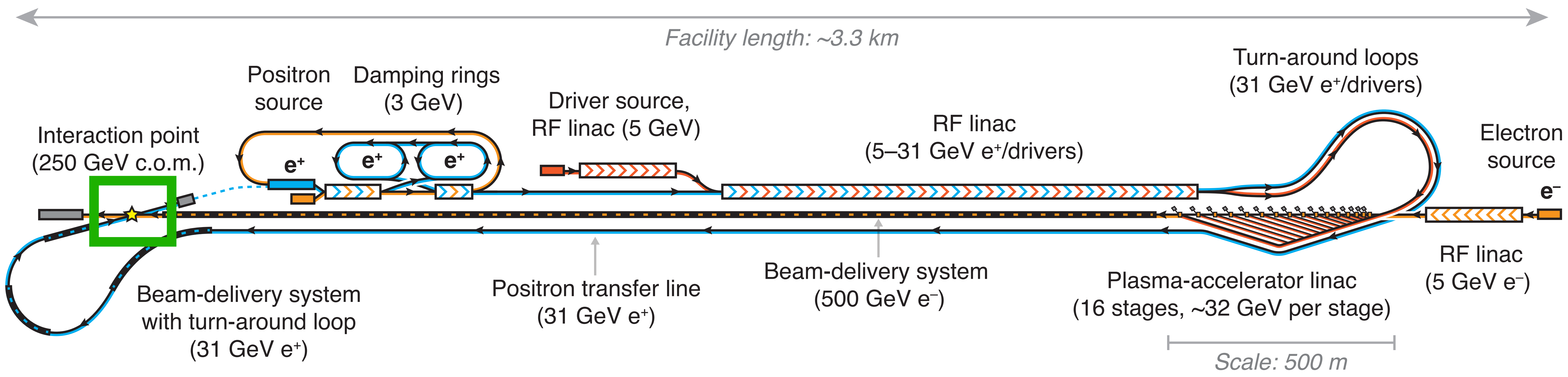
> Detector optimised for asymmetric energies (see Brian's talk)



ZEUS detector at HERA



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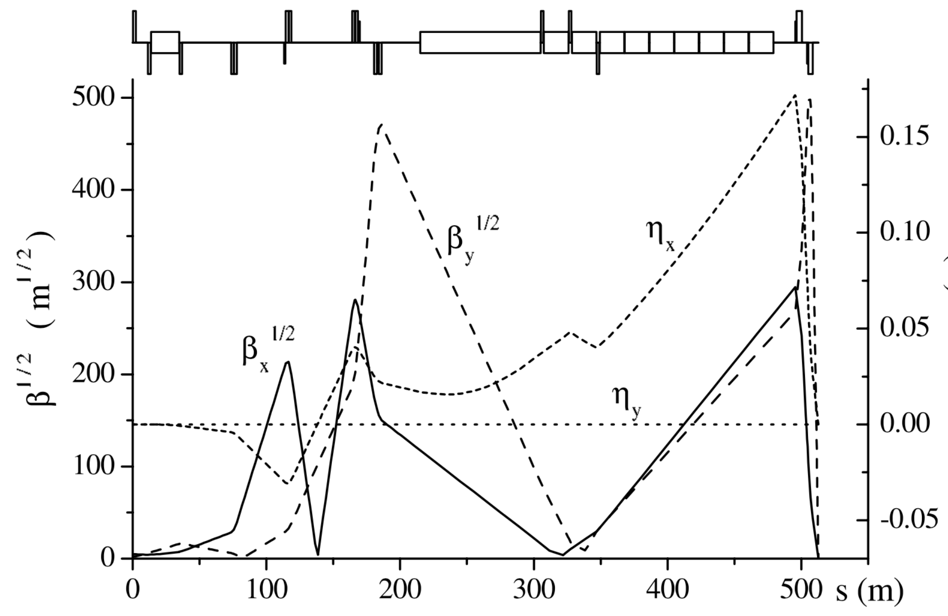
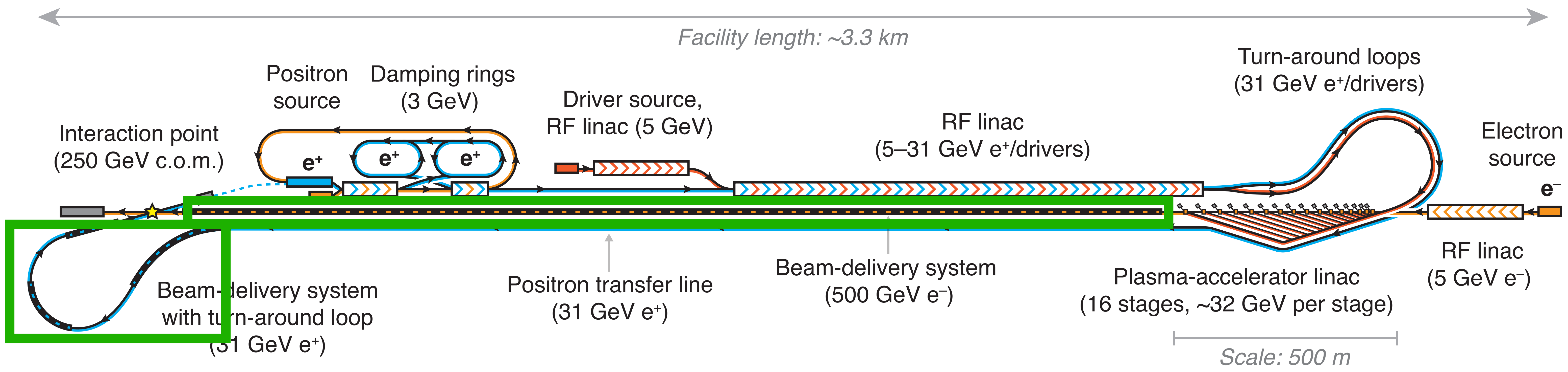


*From: Raimondi & Seryi, PRL **86**, 3779 (2001)*



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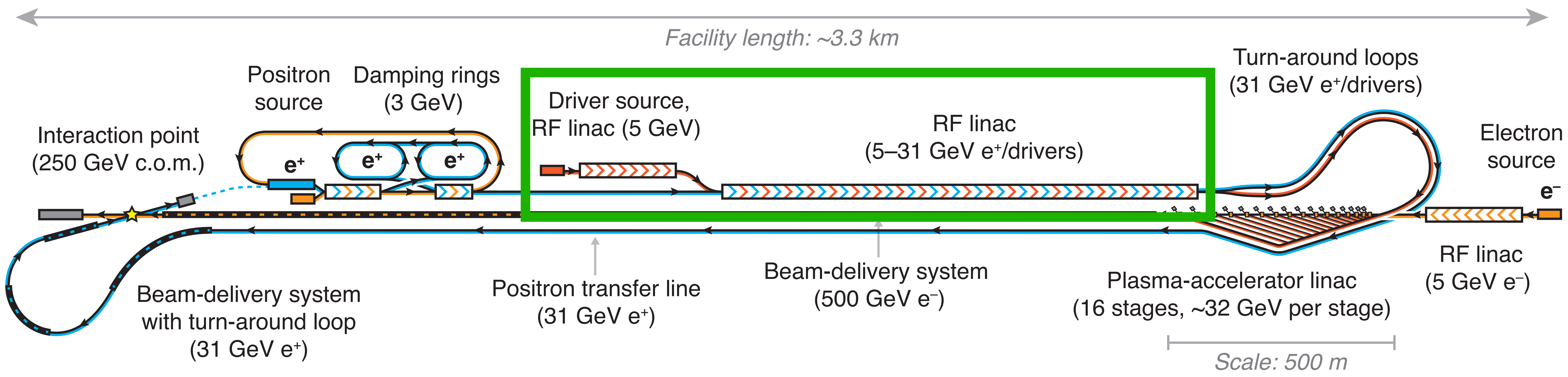
- High-efficiency (heavily beam loaded) RF linac with PWFA-compatible beams

- ***Conventional accelerator expertise required!***



Rough timeline for HALHF (and beyond)

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- Upgrade path toward multi-TeV relies on concepts that need **ongoing parallel R&D**
  - **e^+ acceleration, high-efficiency lasers, nm-level emittances, more compact BDS**

Important note: **Most R&D toward HALHF is driver-agnostic**

- **Key to continue funding existing plasma-accelerator test facilities (regardless of driver technology)**
  - *Most R&D can be performed independent of driver used*
  - *Too many R&D topics for one facility to focus on simultaneously*
- If high-efficiency lasers become available, these can be highly relevant to multi-TeV colliders

	Timeline (approximate/aspirational)		
	0–10 years	**10–20 years**	**20–30 years**
Single-stage accelerators (proton-driven)	**Demonstration of:** Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon search, strong-field QED experiment, etc. (50–200 GeV e^-)	*(Facility upgrade)* ↓ — Legend: *R&D (exp. & theory)*; *HEP facility (earliest start of construction)*
		Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy-frontier collider** 10 TeV c.o.m. electron–proton collider

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Multistage accelerators (Electron-driven or laser-driven)	**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)*
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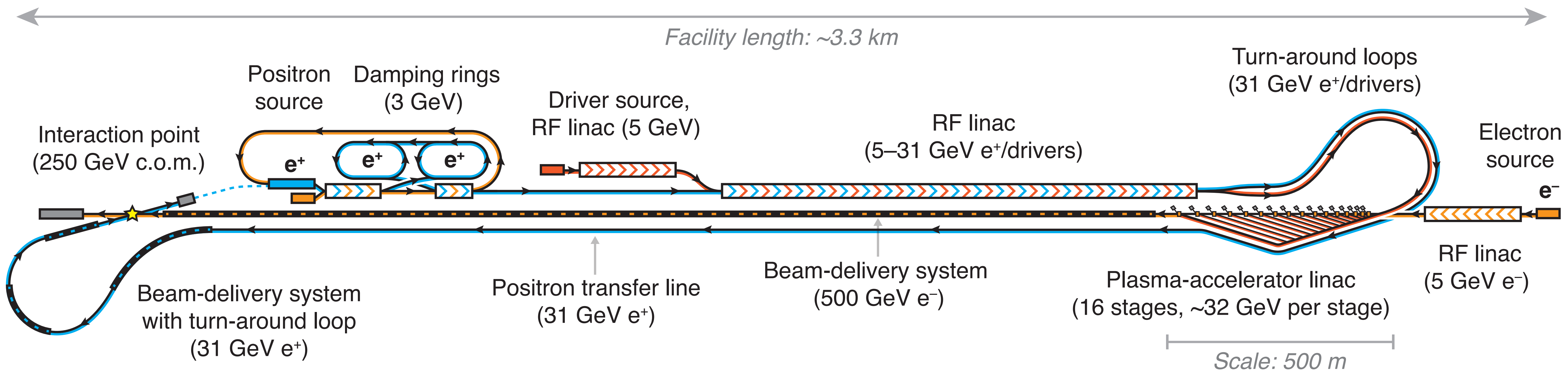
R&D required for future colliders	Demonstrable in Single Stage			Demonstrable in Multi-stage	
	Proton-driven	Electron-driven	Laser-driven	Electron-driven	Laser-driven
Electron beams with HEP relevant energies	3.2			1.1, 1.2	1.3
Acceleration in very long plasma	3.2				
Plasma uniformity (long. & trans.)	3.2	3.1, 2.3	2.3, 2.4		
Preserving injected beam quality: emittance, charge, energy spread, spin polarisation		3.1	1.5, 2.4	3.1	1.5, 2.4
Stabilisation (active and passive)		3.1	2.4	3.1	2.4
Ultra-low emittance beams					
Advanced beam-delivery systems	1.6	1.6	1.6	1.6	1.6
External injection and timing		3.1	2.4	3.1	2.4
Positron beams for collider	1.4	1.4	1.4		
High rep-rate targetry with heat management		2.3, 3.1	2.1, 2.3, 2.4		
Facility sustainability	1.7	1.7	1.7	1.7	1.7
Temporal plasma uniformity & stability	3.2				
Driver removal		3.1	2.4	3.1	2.4
High rep-rate, high wall plug efficiency drivers			2.1, 2.2		2.1, 2.2
Inter-stage beam coupling and timing				3.1	2.4
Driver coupling and removal (plasma mirrors)				3.1	2.4
Total system design with end-to-end simulations				1.1, 1.2	1.3

Not applicable
Not feasible
Not part of the program
Technically feasible

Conclusions

Preprint: Foster, D'Arcy & Lindstrøm, arXiv:2303.10150 (2023)



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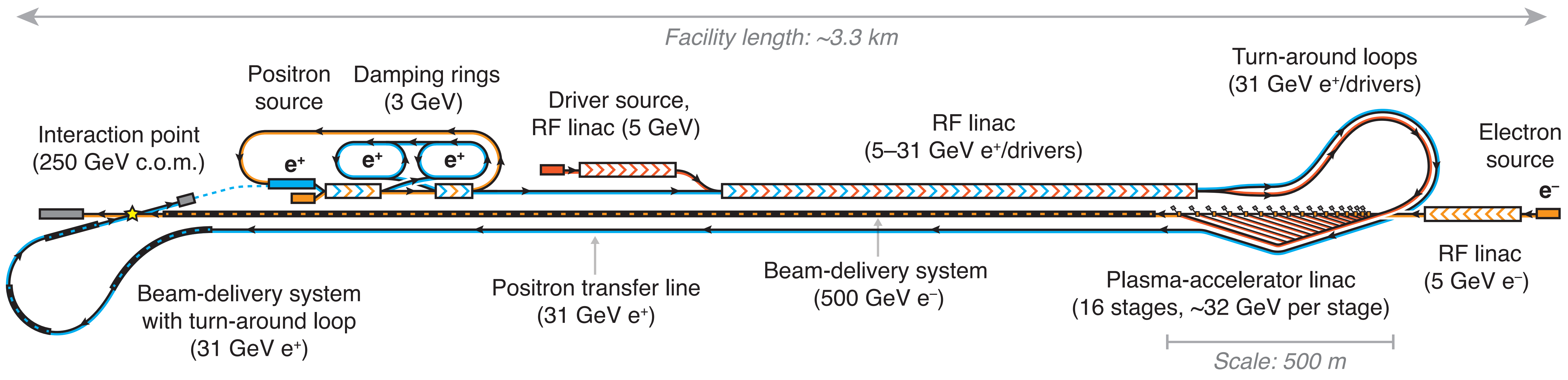

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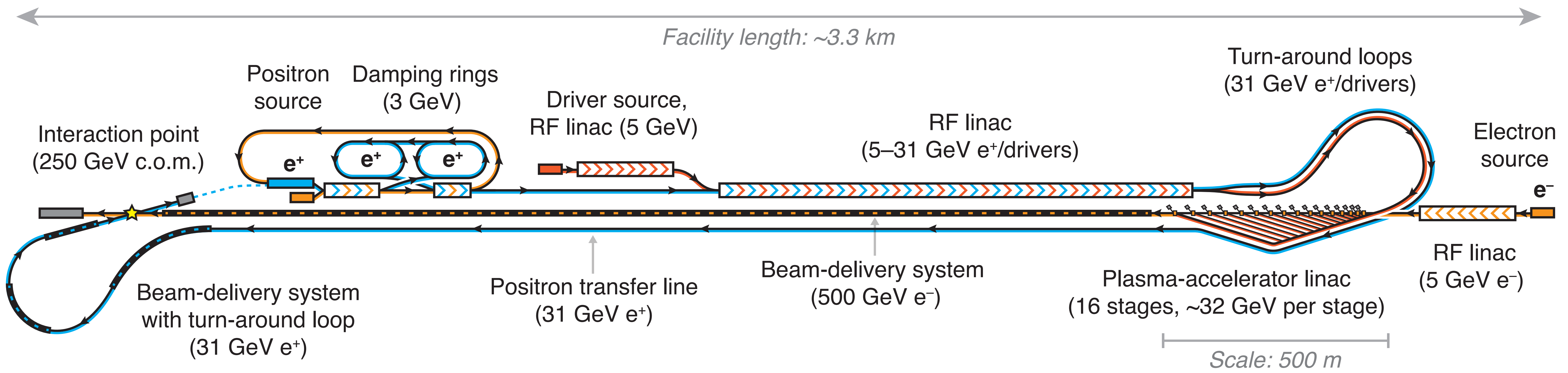

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  - Part of a longer-term technology development of plasma-accelerators
- **Much targeted R&D still required (e.g., staging, beam quality, beam power)**
  - Continued funding of existing test facilities (regardless of driver technology) is key