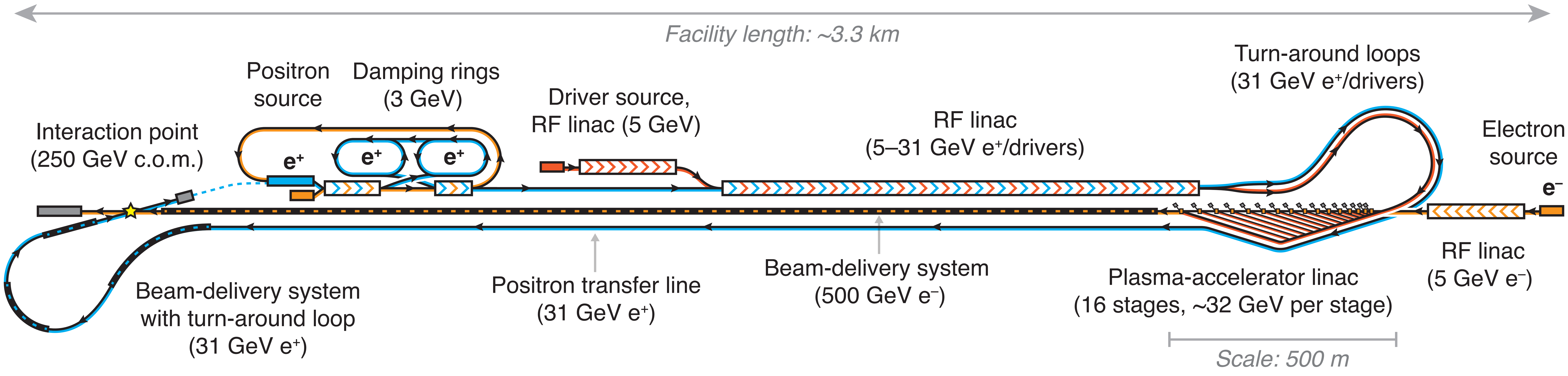


HALHF:

A Hybrid, Asymmetric, Linear Higgs Factory

Richard D'Arcy

University of Oxford

Brian Foster, Carl A. Lindstrøm

University of Oxford/DESY & University of Oslo

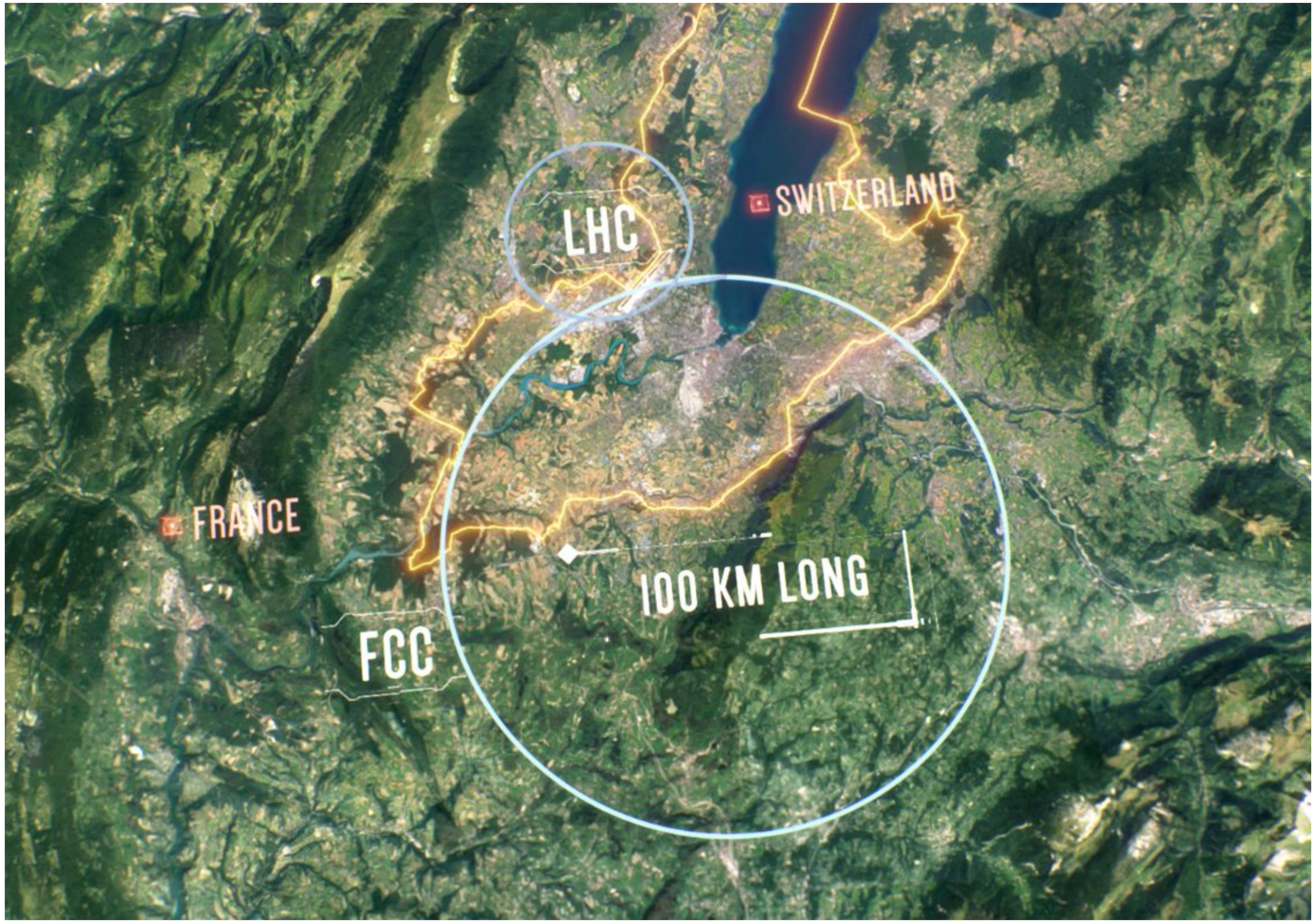
15th May 2024 | RAL Particle Physics Seminar

Outline

- Motivation
- Concept
- Design
- Upgrade paths
- R&D plan
- Timeline & Staging
- Conclusions

Motivation: Realising the next generation of HEP machines

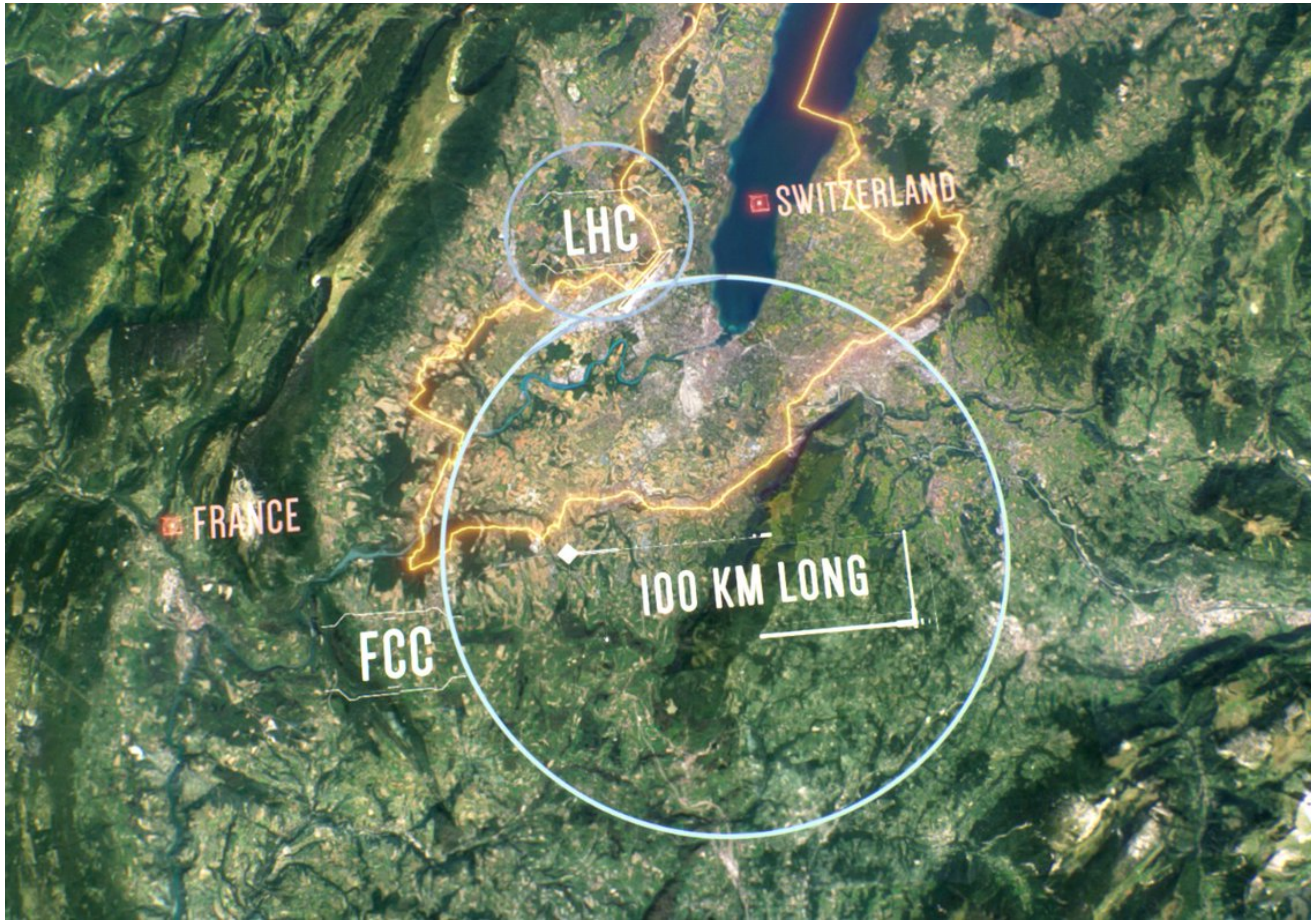
- Post-LHC era approaches (~2040)
- **Next**: Electron–positron collider
  - Precision studies of the Standard Model (Higgs, etc.)



Future Circular Collider. *Source: CERN*

Motivation: Realising the next generation of HEP machines

- 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



Future Circular Collider. *Source: CERN*

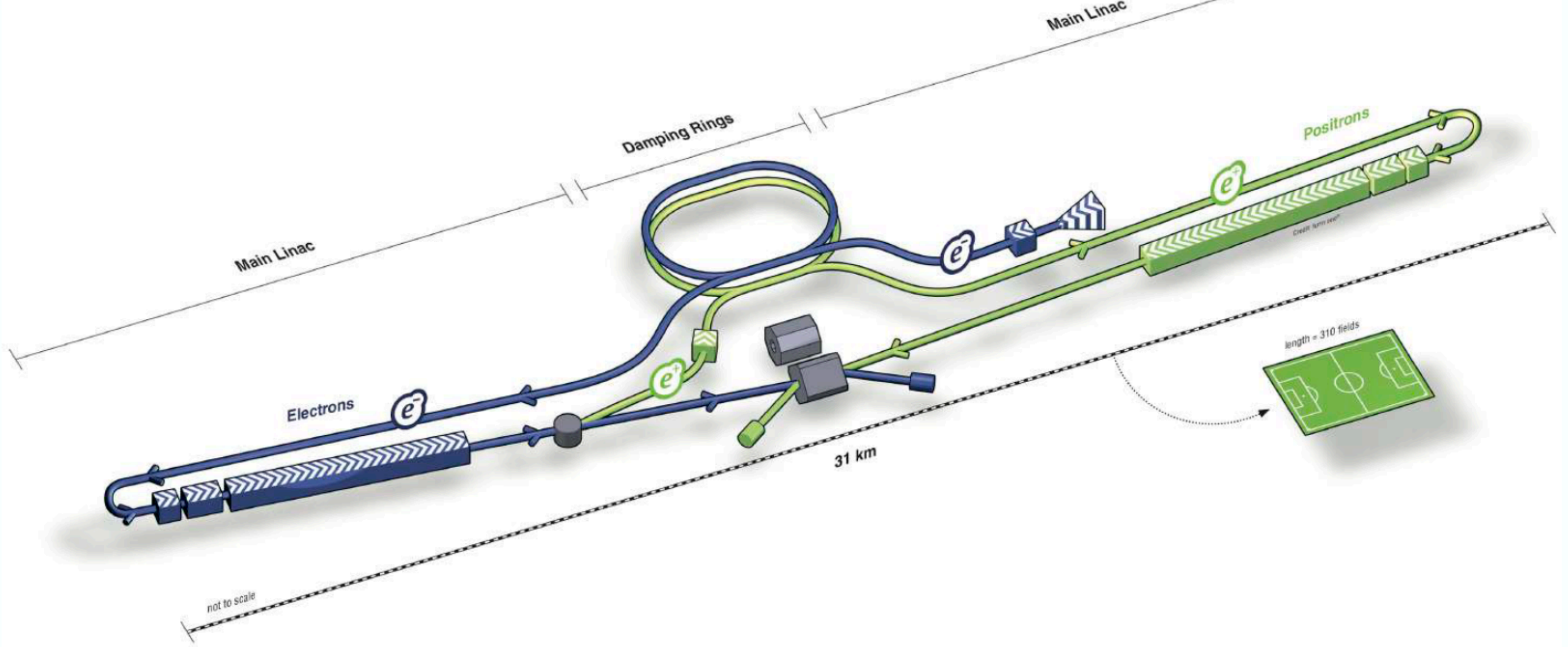
Challenge: Current accelerator technology at a performance plateau

Radio-frequency cavity

Size of high-energy machines driven by RF accelerating gradient (<100 MV/m) → ***expensive!***

International Linear Collider (ILC)

30 km footprint



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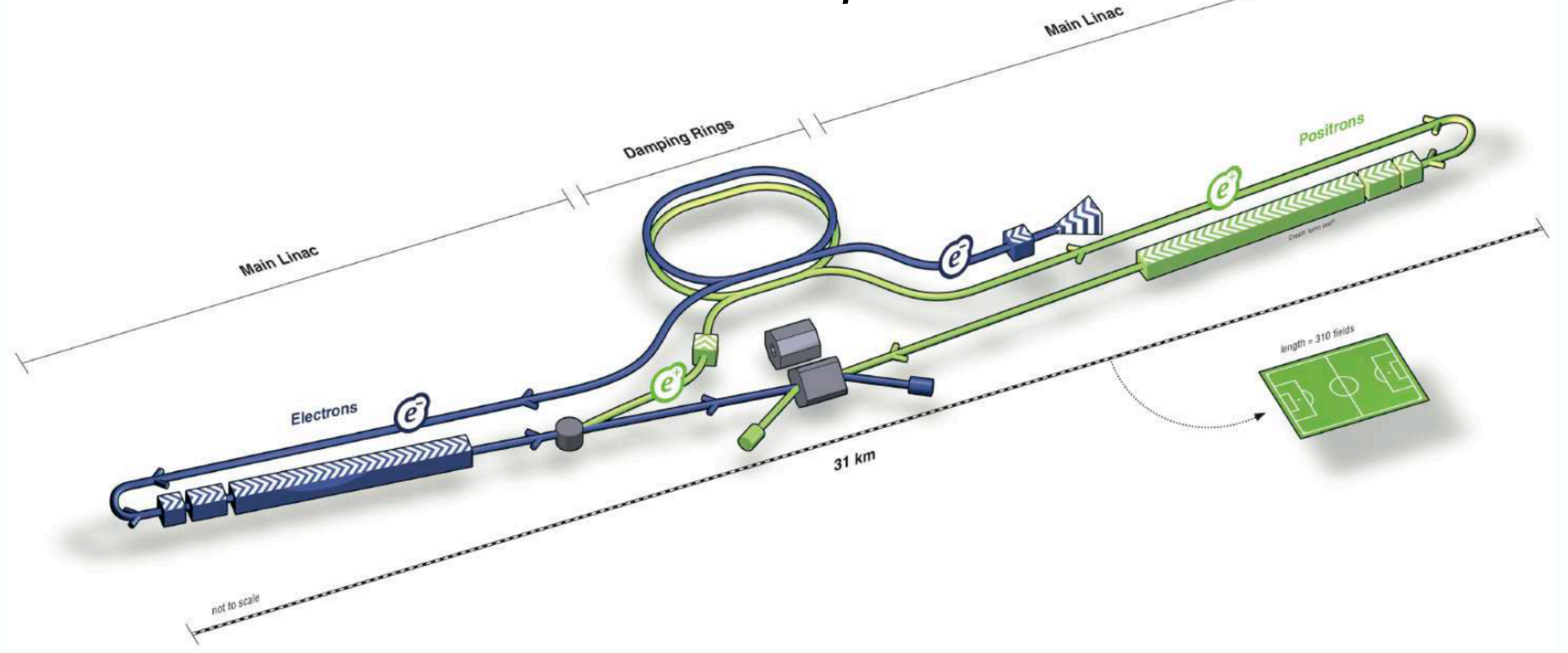


> EU Strategy for Particle Physics 2020:

- *"… **intensification of R&D** is required."*
- e.g. *"Development and exploitation of **plasma acceleration** techniques"*

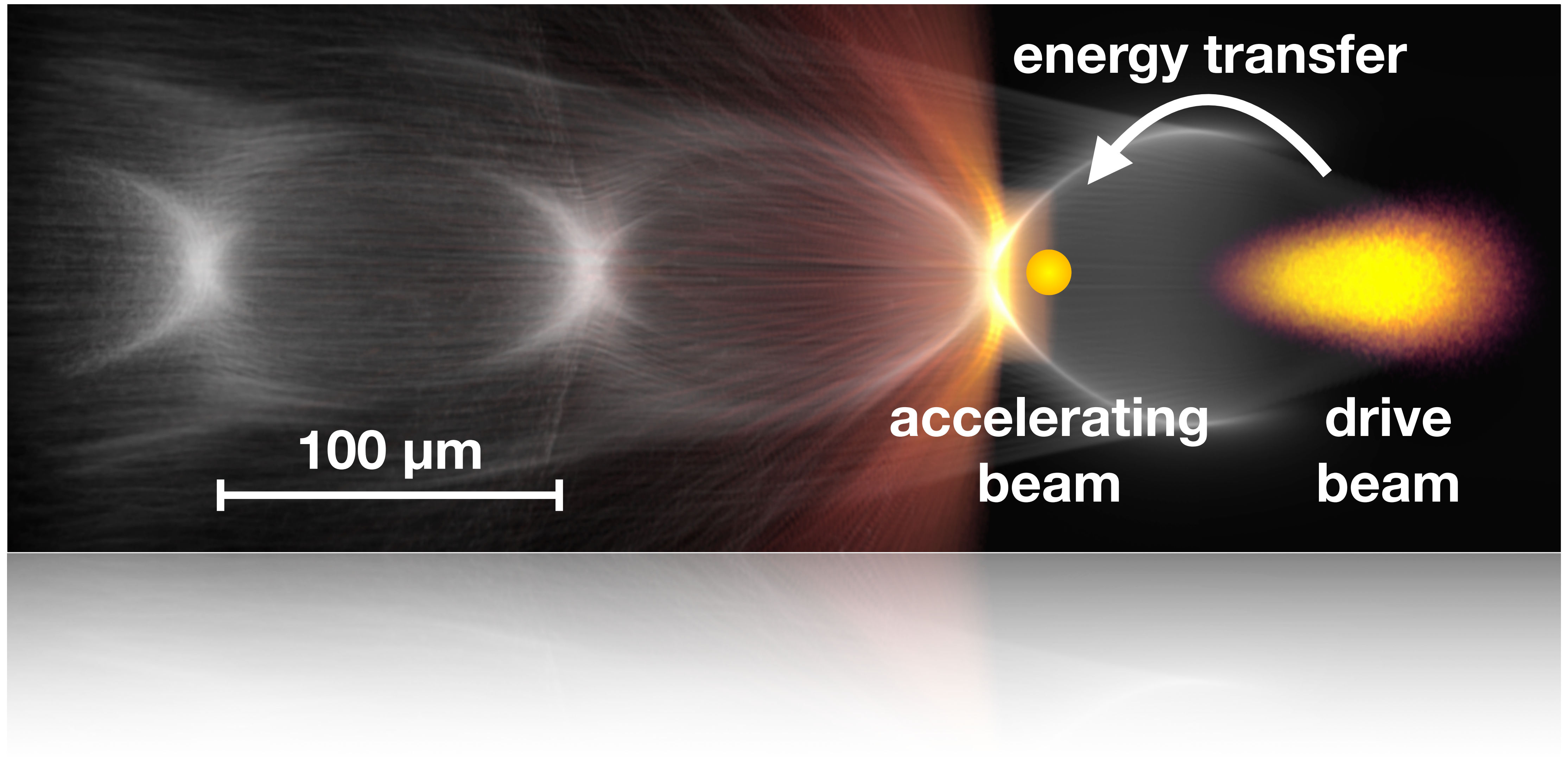
Solution: Plasma Accelerators

Wake excitation

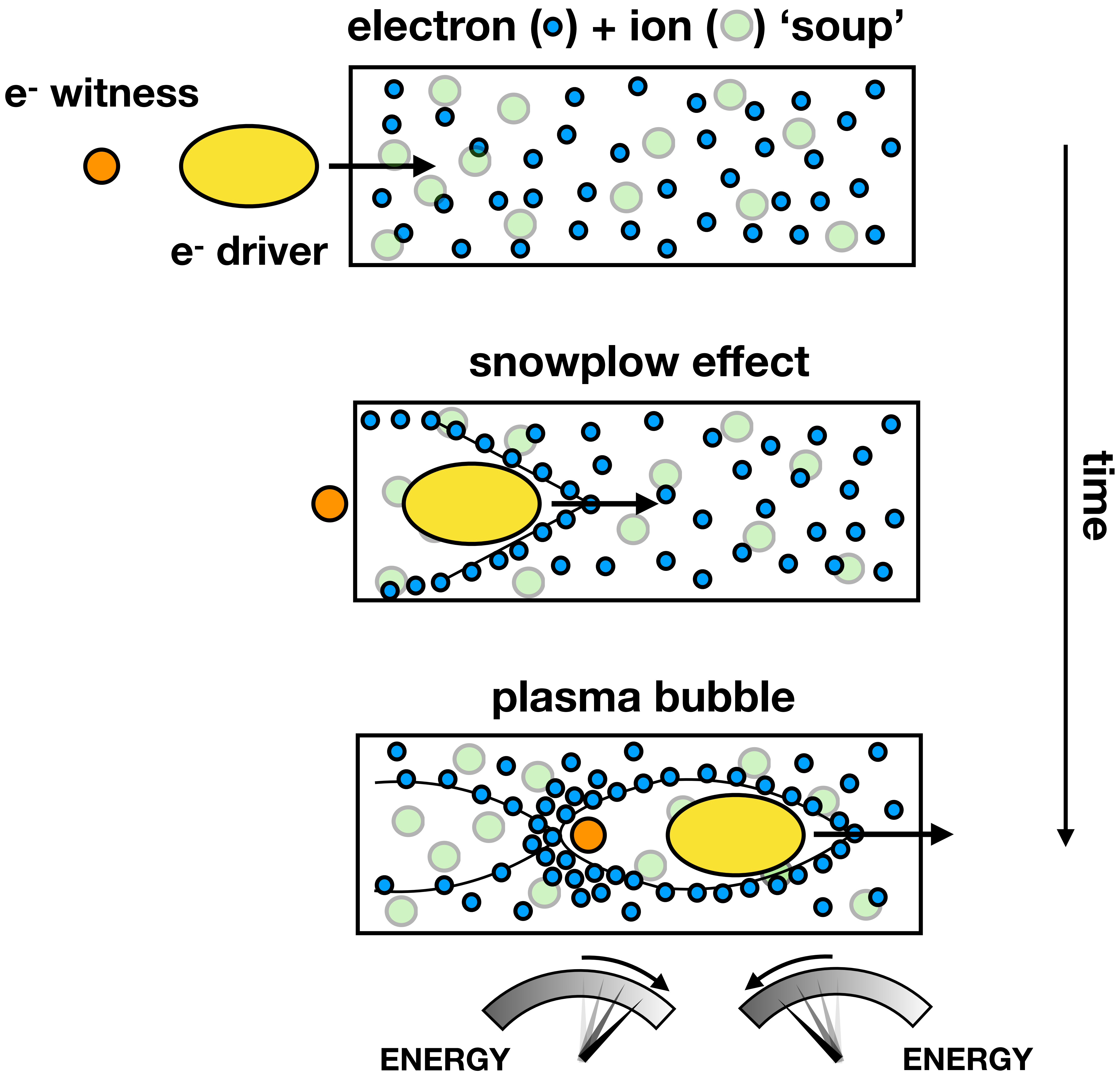
Particle acceleration

Solution: Plasma Accelerators

Charge-density wave in plasma



Harnesses the enormous fields experienced at inter-atomic scales



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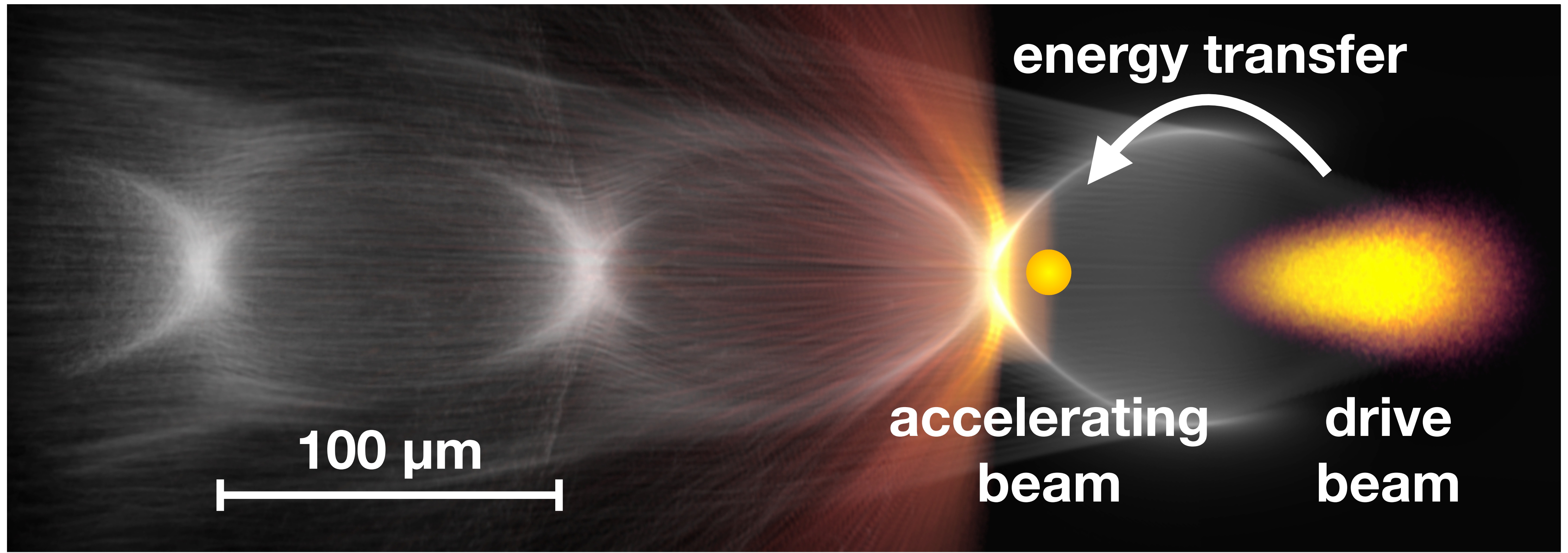
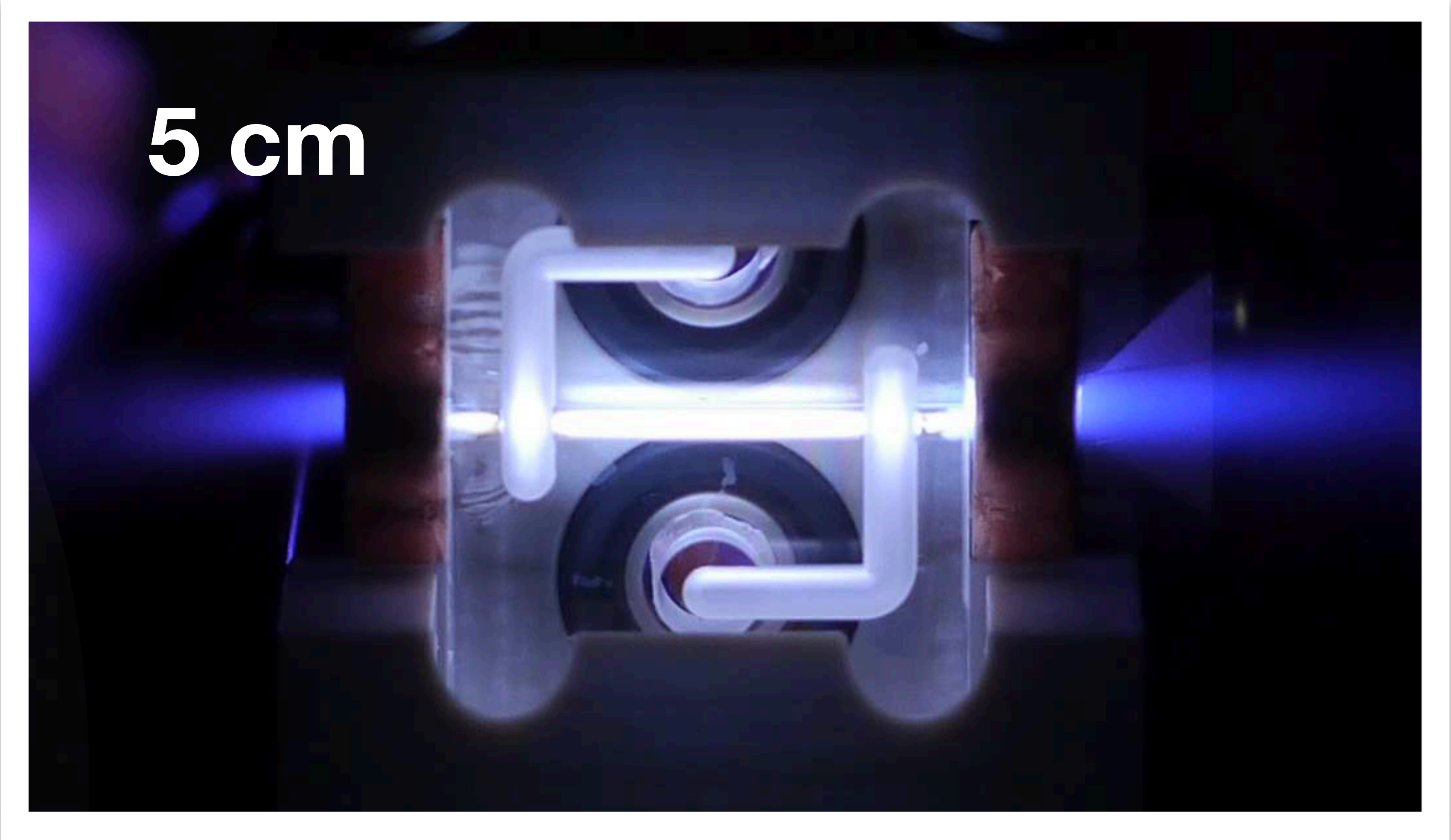


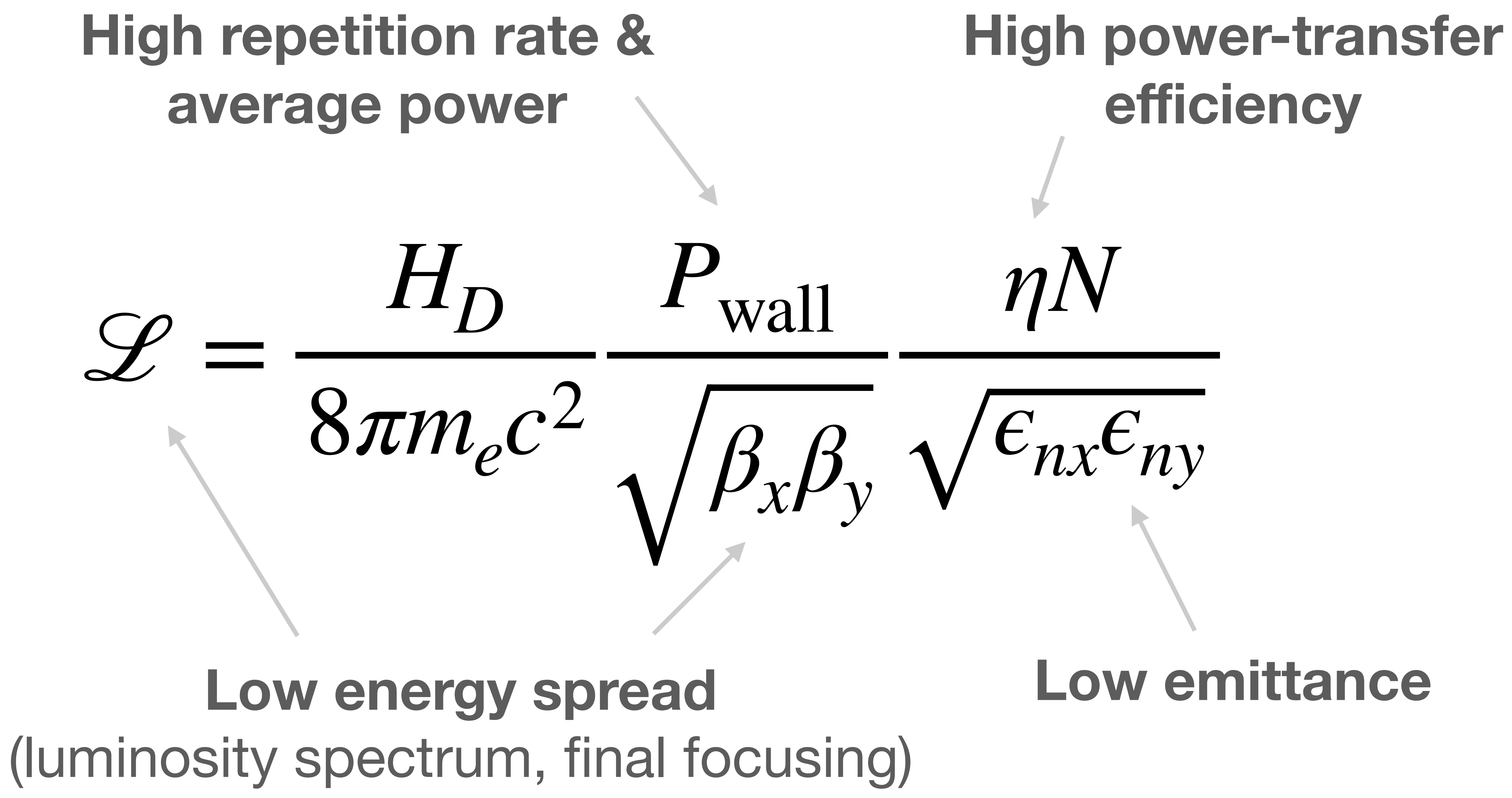
Harnesses the enormous fields experienced at inter-atomic scales

Higher gradients (GV/m or higher) → ***shorter and cheaper accelerators!***



Particle physicists have requirements in addition to high energy

Collider Luminosity



High repetition rate & average power

High power-transfer efficiency

$$\mathscr{L} = \frac{H_D}{8\pi m_e c^2} \frac{P_{\text{wall}}}{\sqrt{\beta_x \beta_y}} \frac{\eta N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

Low energy spread
(luminosity spectrum, final focusing)

Low emittance

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Low energy spread
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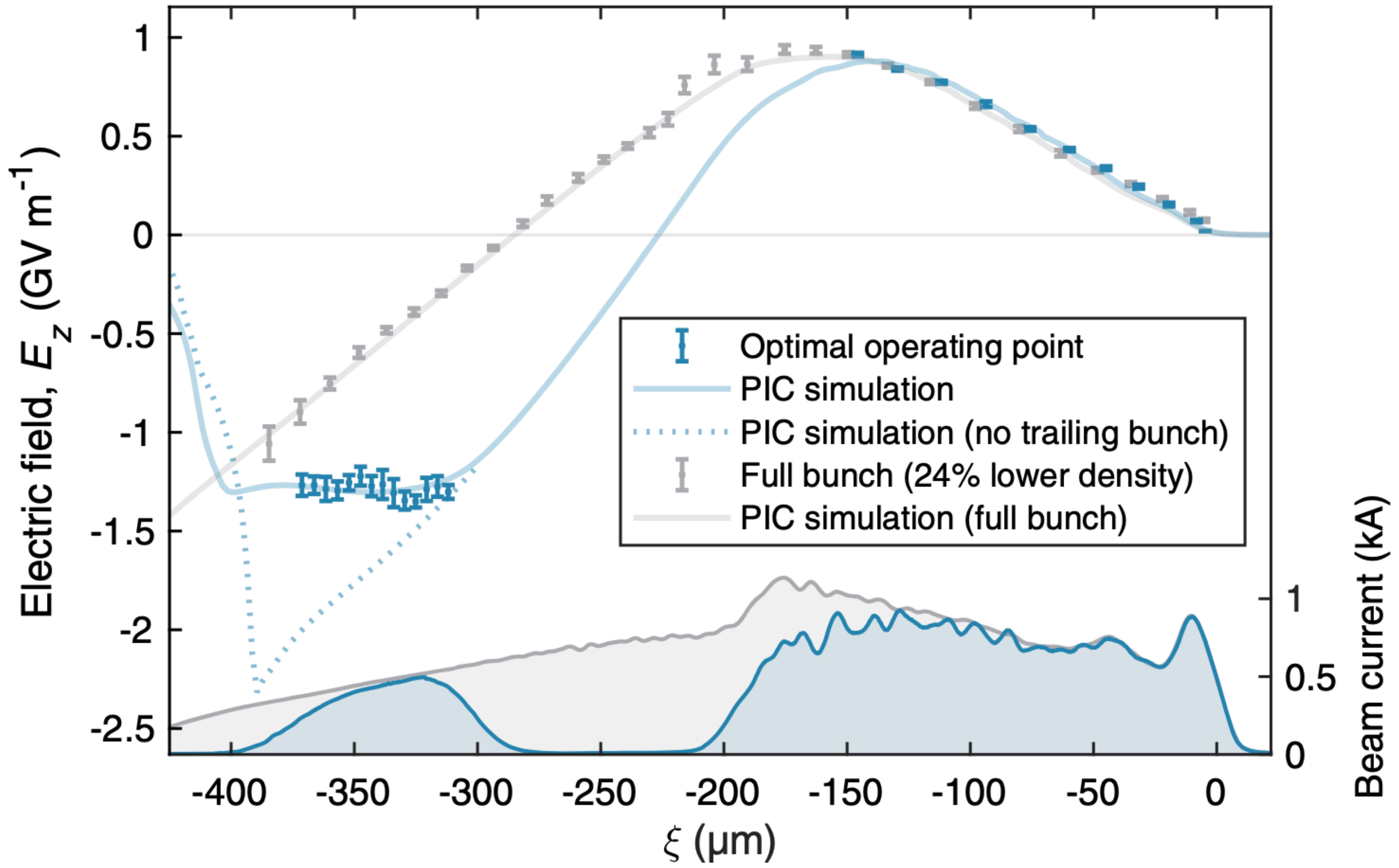
Low emittance

- Excellent experimental progress made in recent years
  - In particular at cutting-edge facilities such as **FLASH**FORWARD▸▸ (DESY, Hamburg)

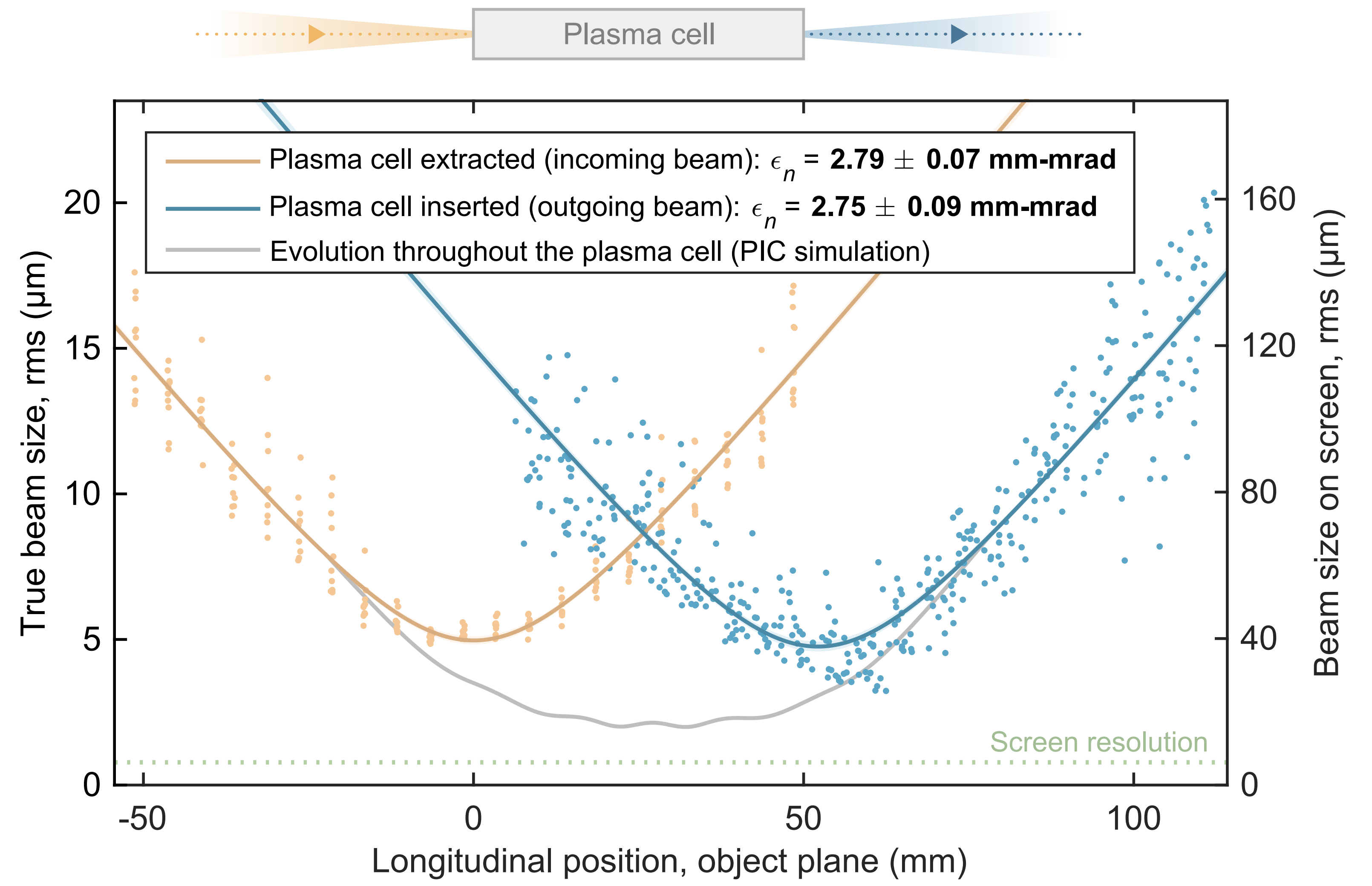
Recent progress in Plasma Accelerator R&D at FLASHFORWARD▸▸

> Towards high beam quality:
  > Energy-spread preservation (**‰-level**)
  > Transverse emittance preservation (**µm-level**)

C.A. Lindstrøm *et al.*, PRL **126**, 014801 (2021)



C.A. Lindstrøm *et al.*, (under review at Nat. Commun.)



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  - [1] Drive Beam ➞ Wakefield (**~50%**)
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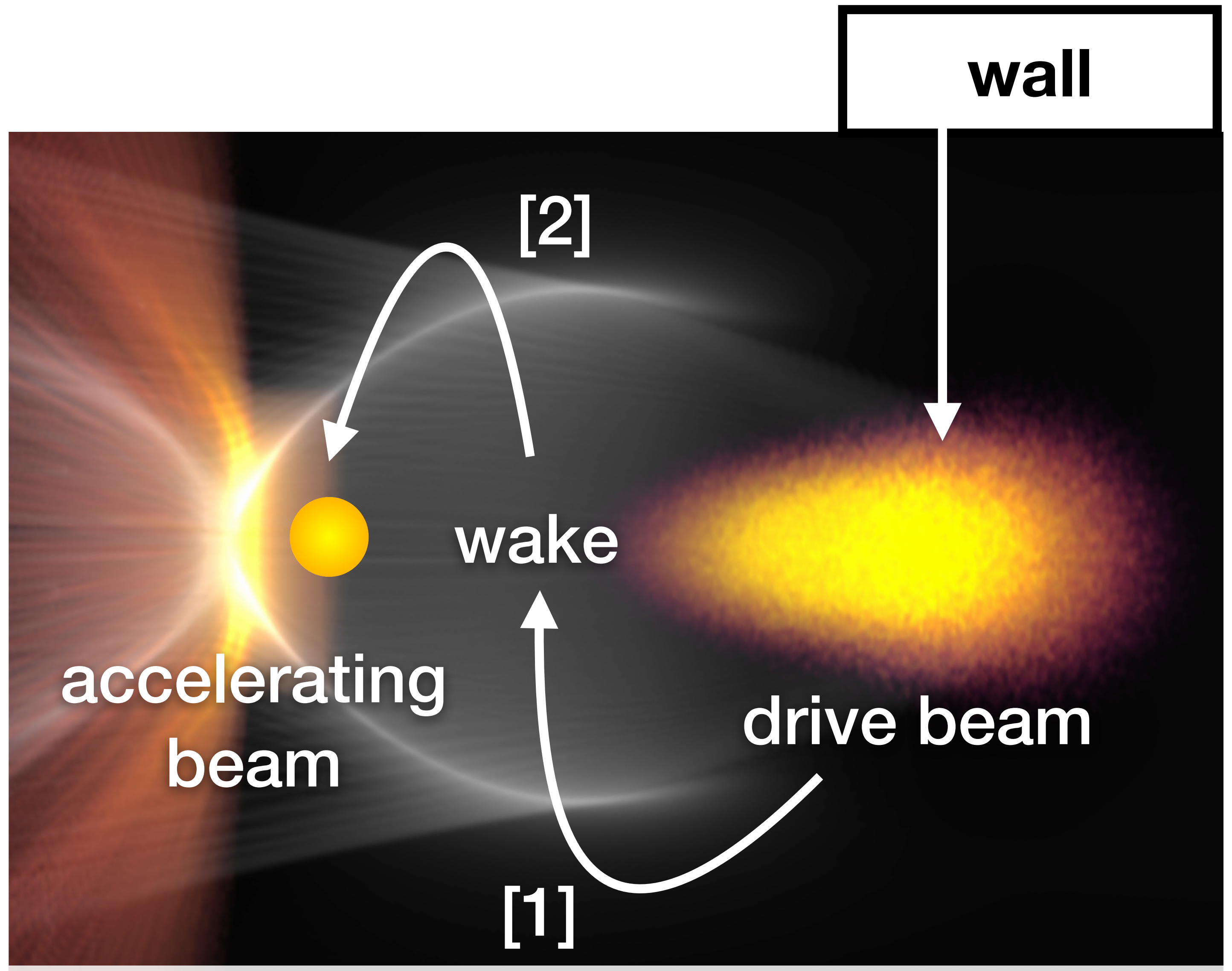
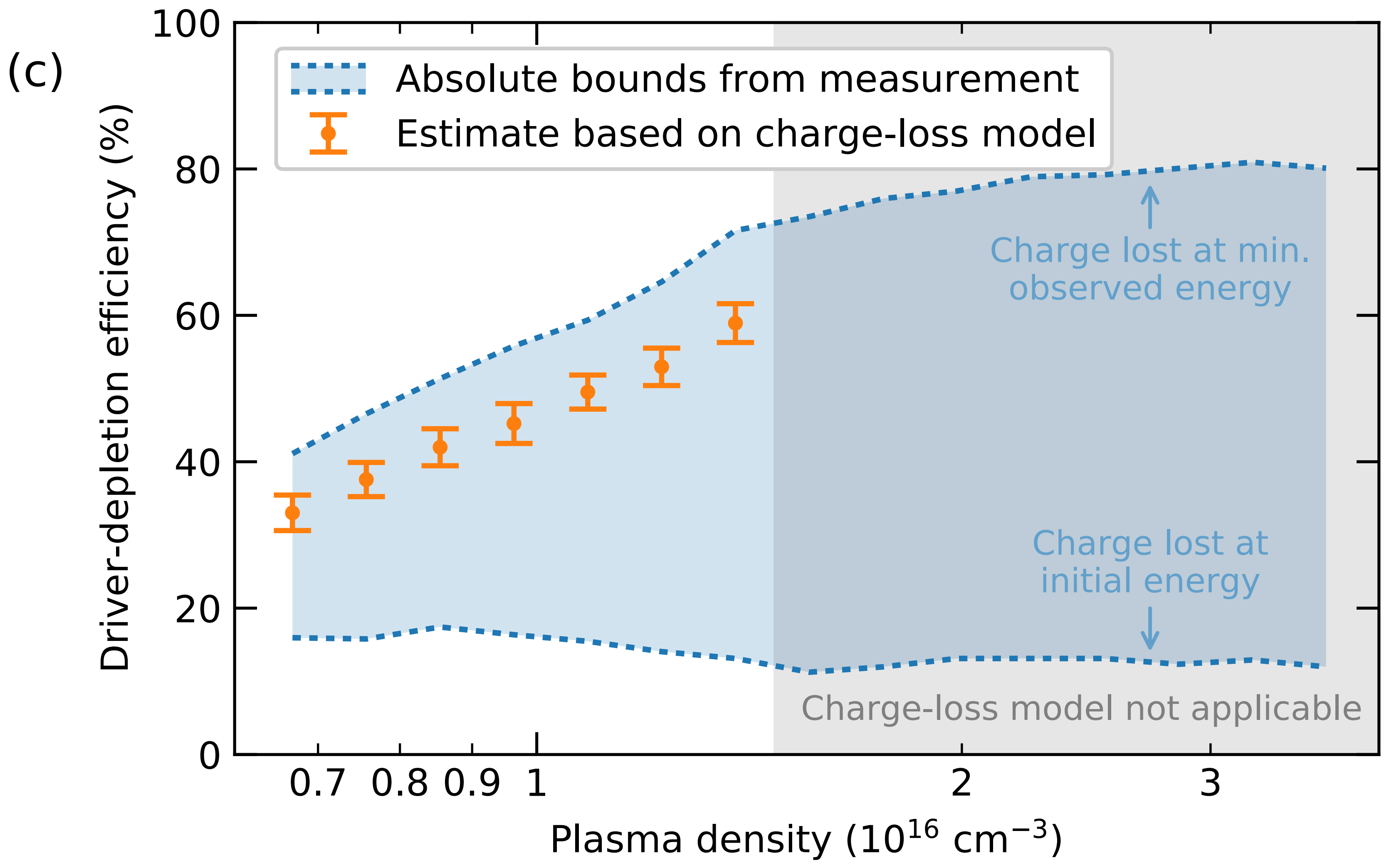


F. Peña *et al.*, (under review at PRL)



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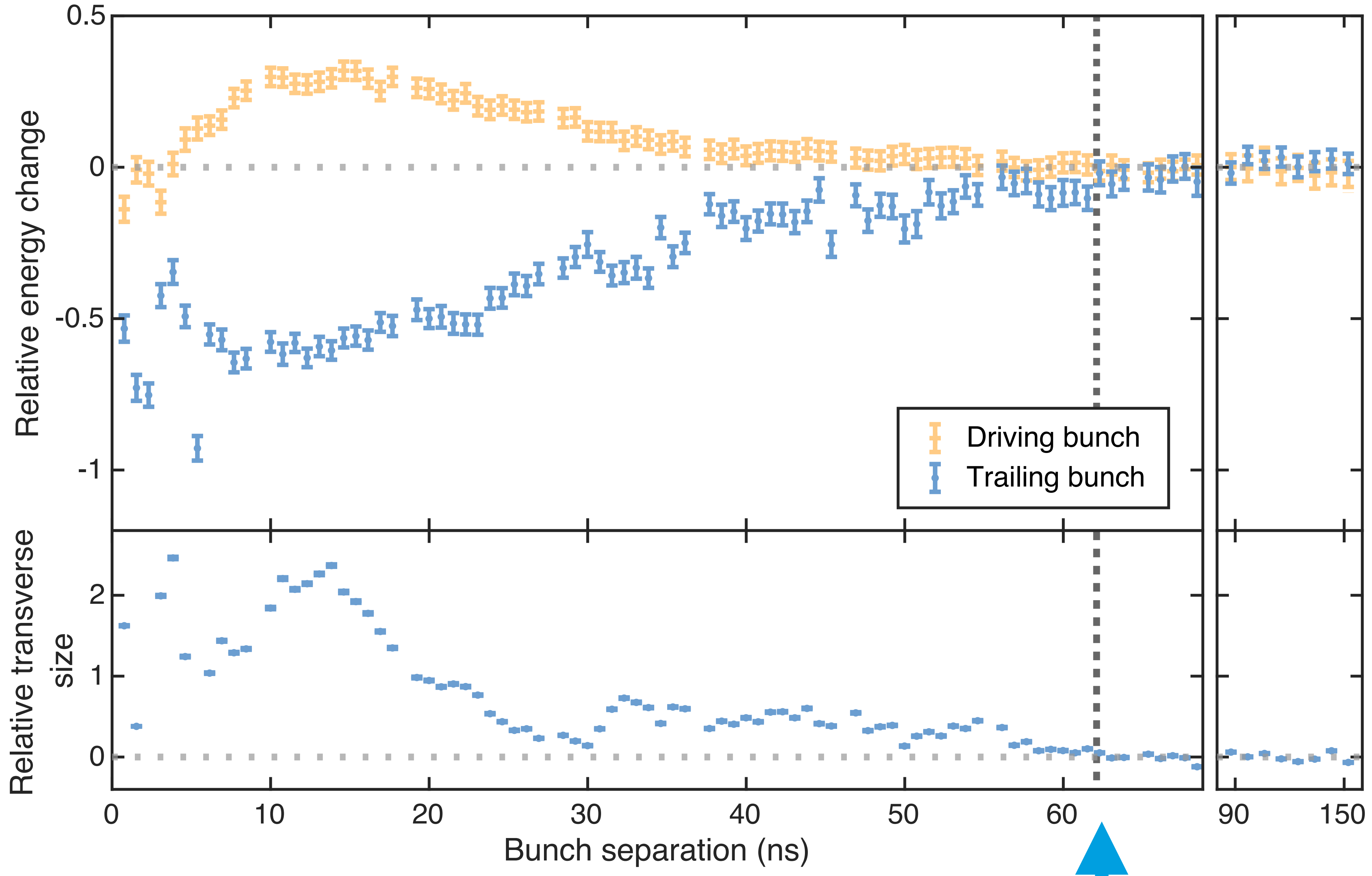
- Towards high repetition rate and average power:
  - Rapid plasma recovery time (**10 MHz ➞ higher than required for ILC**)

R. D'Arcy *et al.*, Nature **603** (2022)



plasma recovery at 63 ns

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Developing a credible plasma-based e^+e^- collider design

- Excellent experimental progress suggests hope for a plasma-based e^+e^- collider
- Several proposals over the past decades:
  - *Rosenzweig et al. (1996)*
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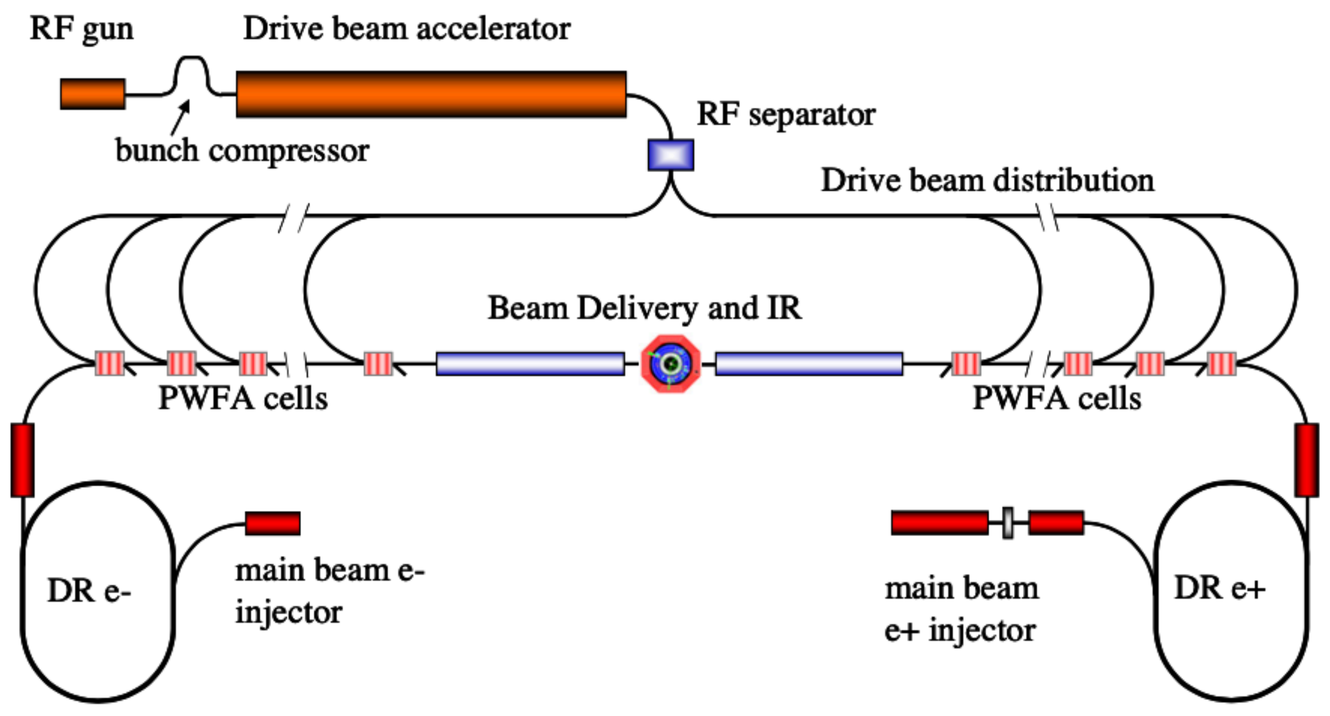
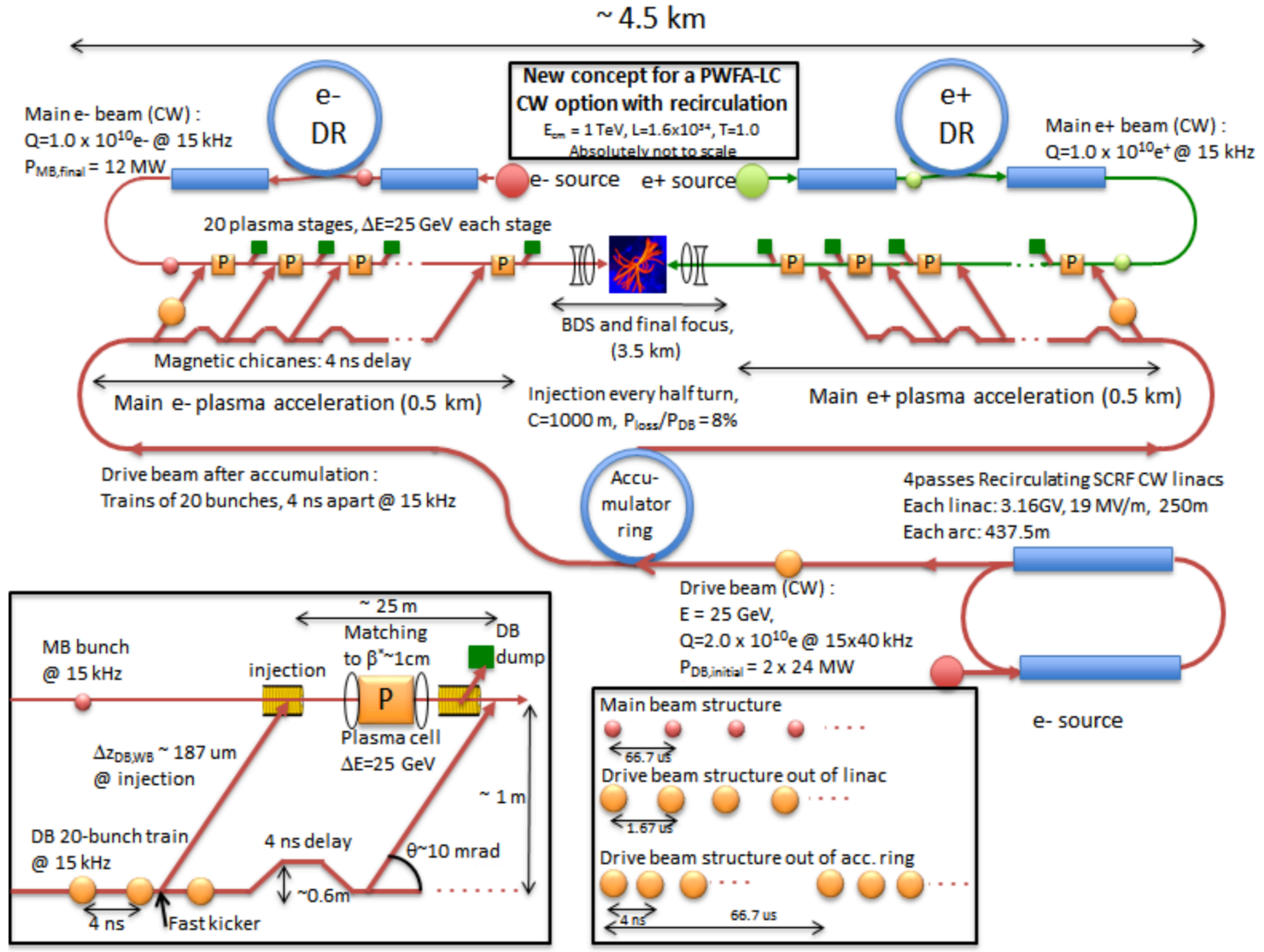


Source: Pei et al., Proc. PAC (2009)



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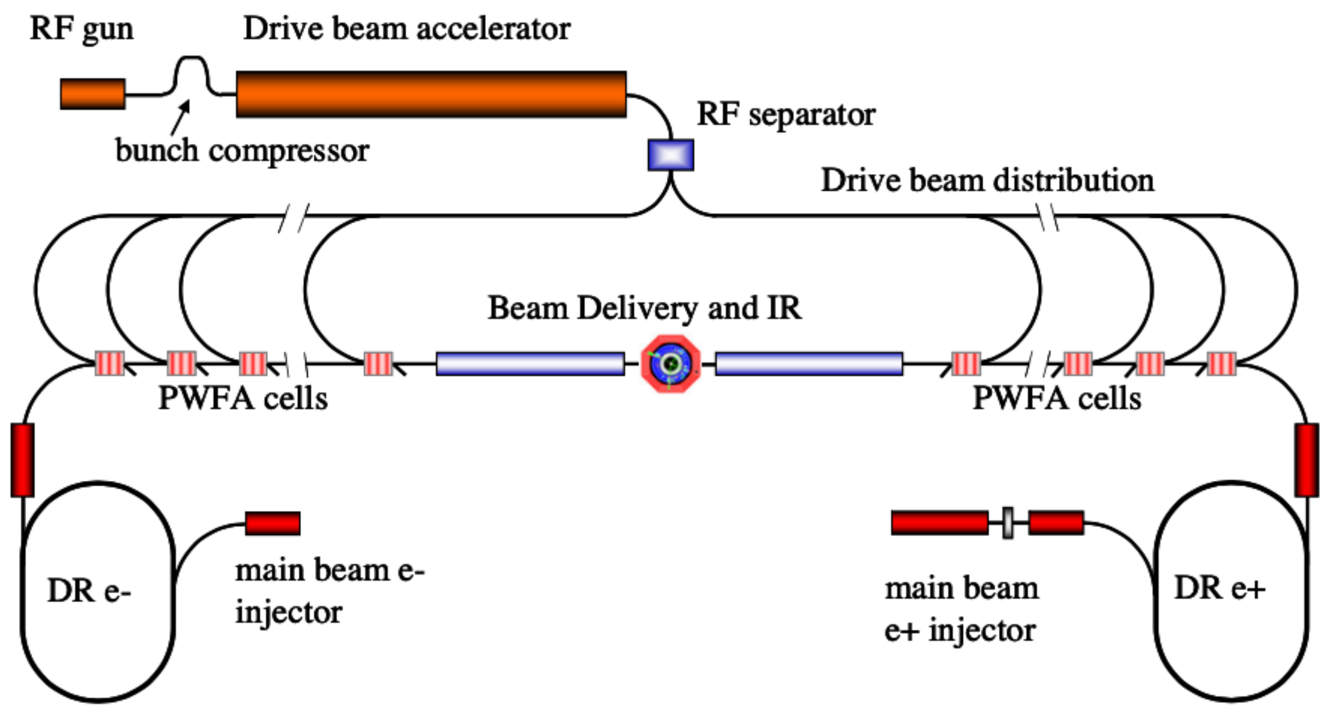
- **Very useful exercises to focus R&D**
- One key stumbling block has been identified…



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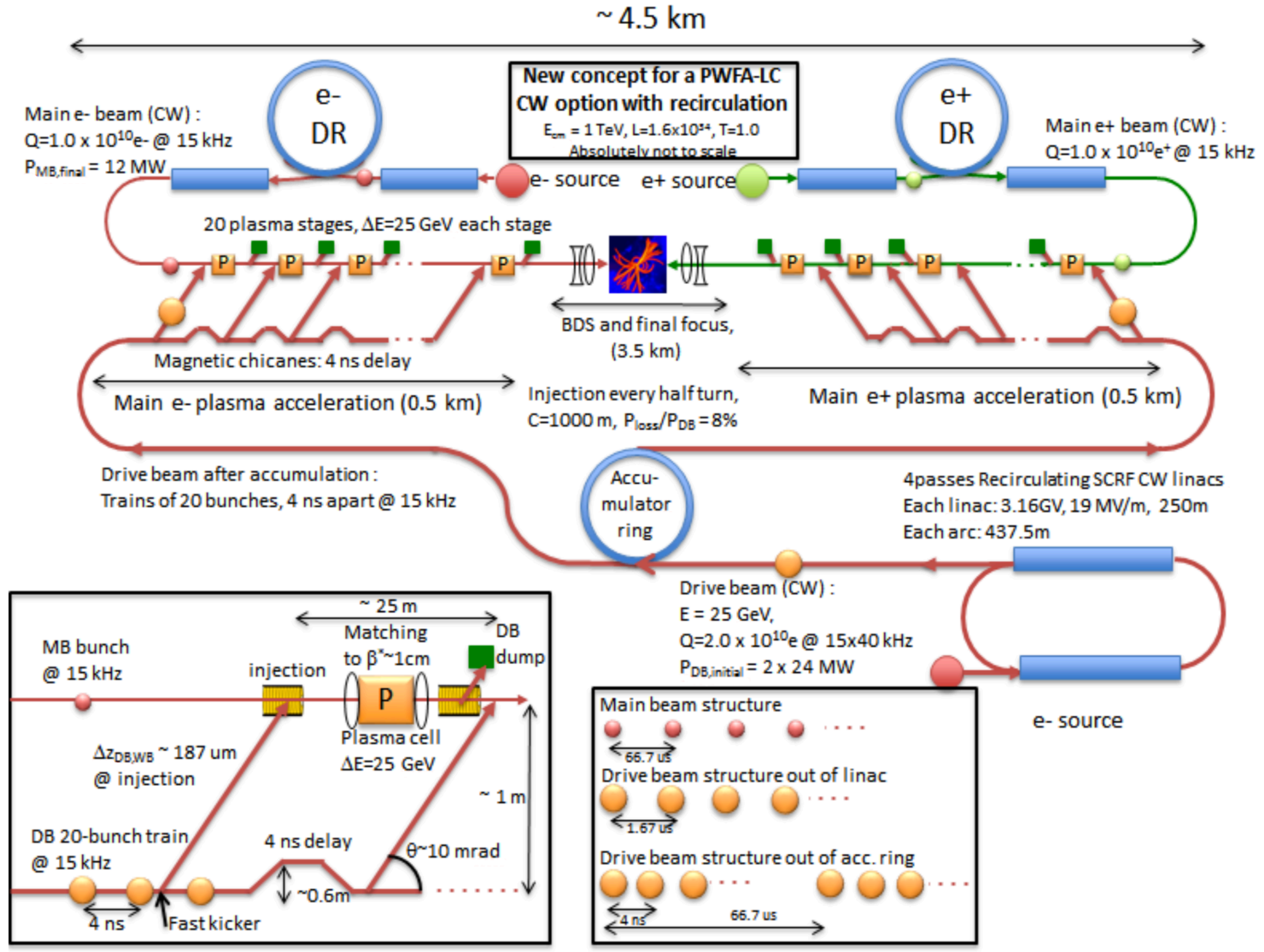

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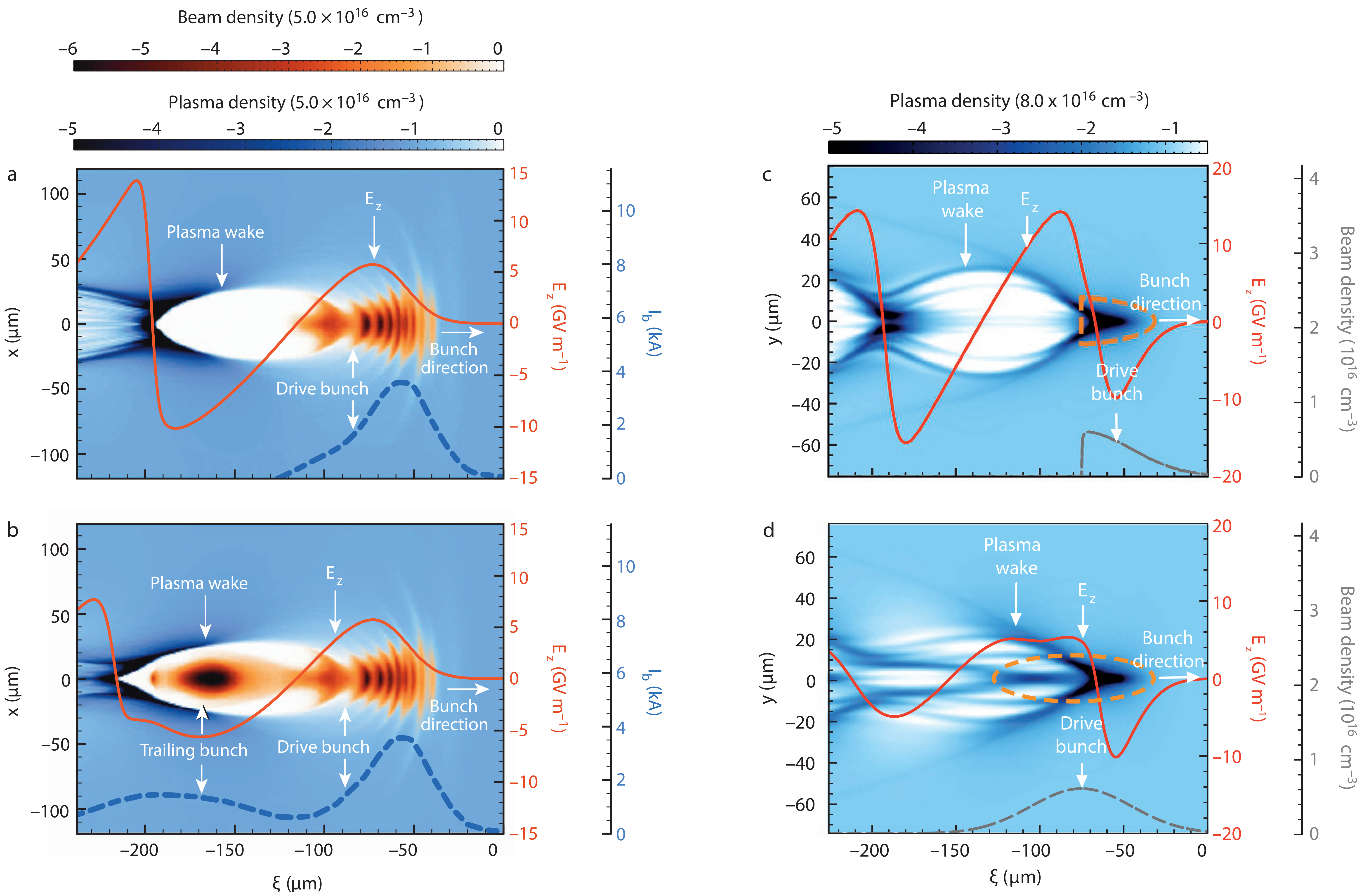
Main problem: Positron acceleration in plasma

- **Plasma** = charge asymmetric
  - No ‘blowout regime’ for e^+



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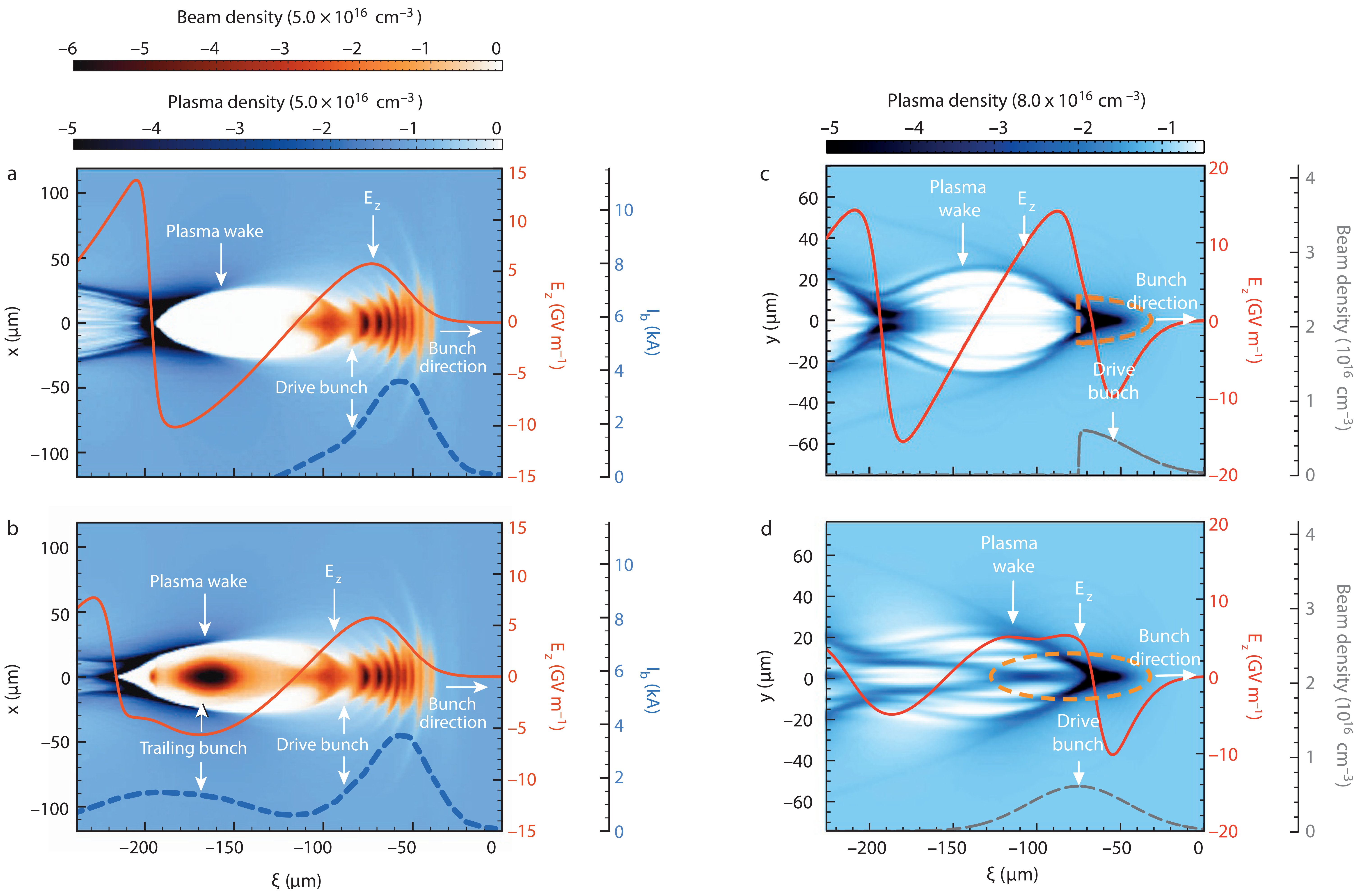

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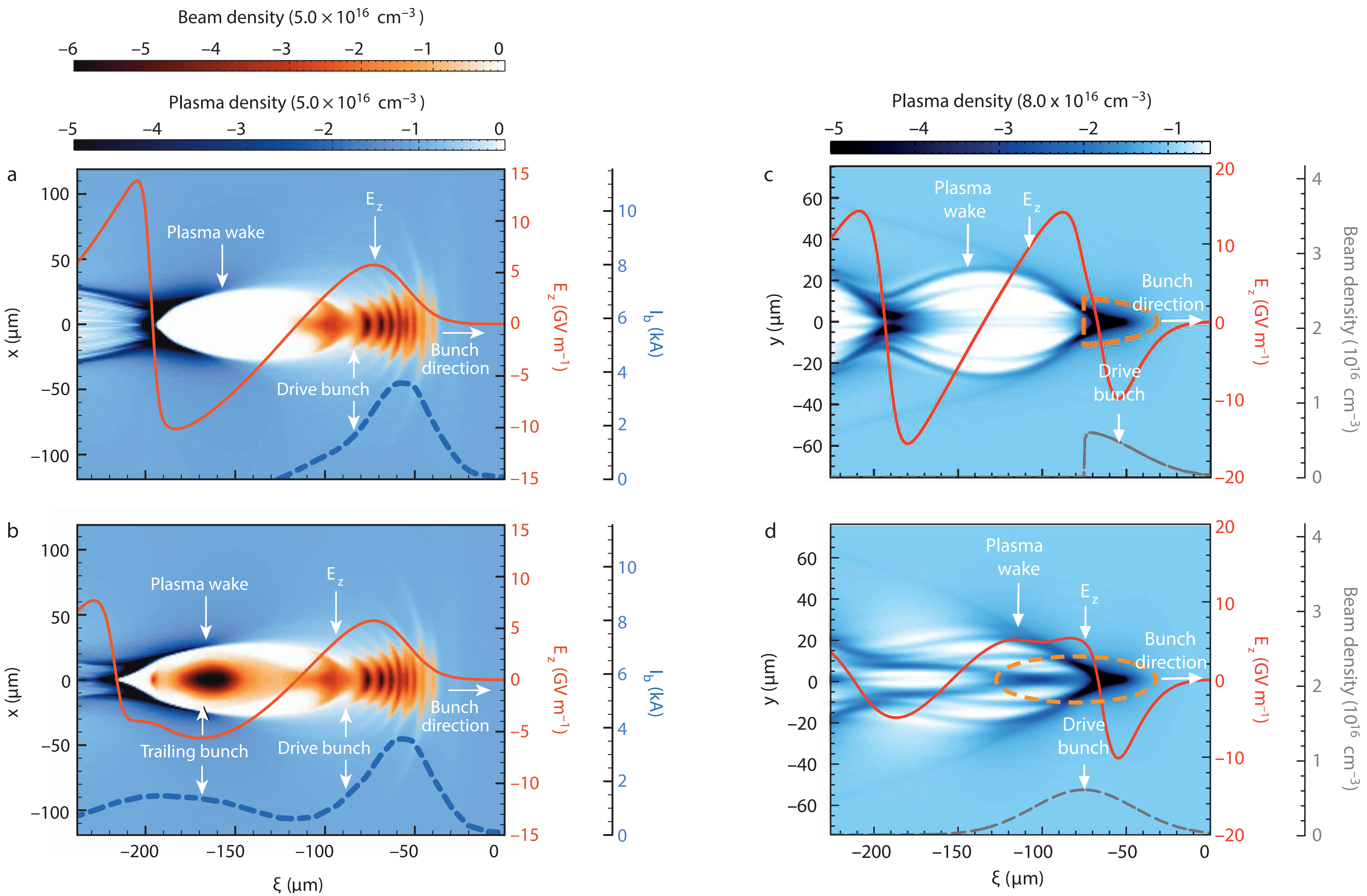
- Currently, *luminosity per power* still ~1000x below RF and e^-
- **Main challenge**: *Electron motion* (equivalent to ion motion for e^- but plasma electrons are lighter)



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The pragmatic approach:

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

The pragmatic approach:

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

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

Can we use **asymmetric e^+/e^- energies** to reduce cost?

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

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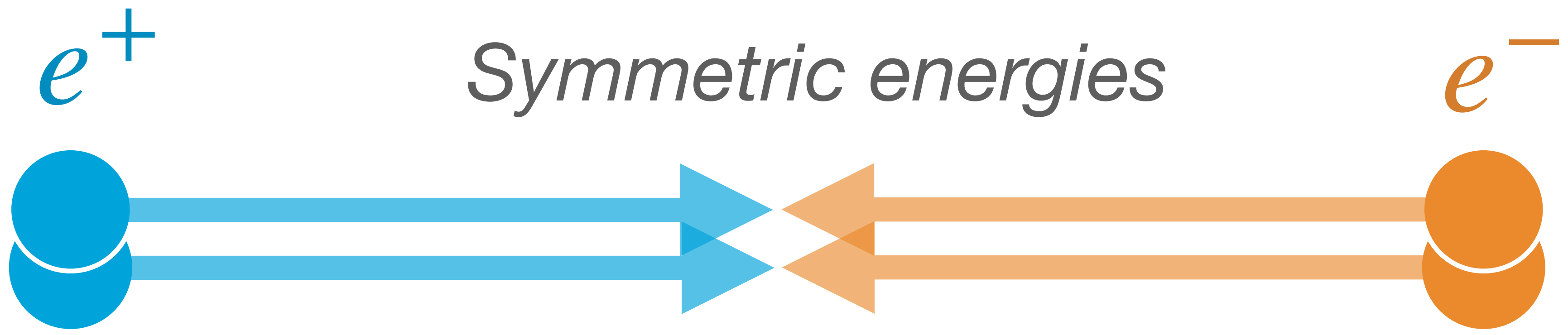

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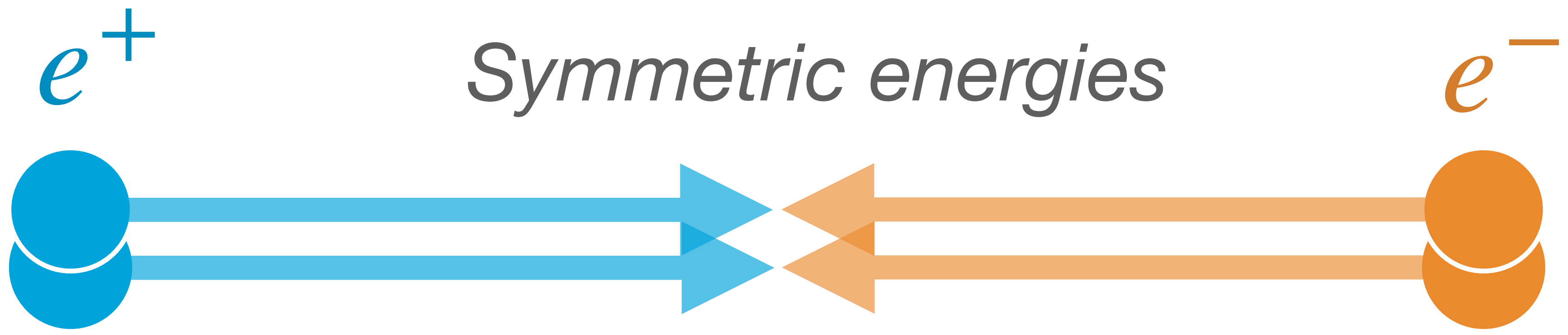
- Electron (E_e) and positron energies (E_p) must follow:
  - However, the collision products are boosted (γ):

$$E_e E_p = s/4$$

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



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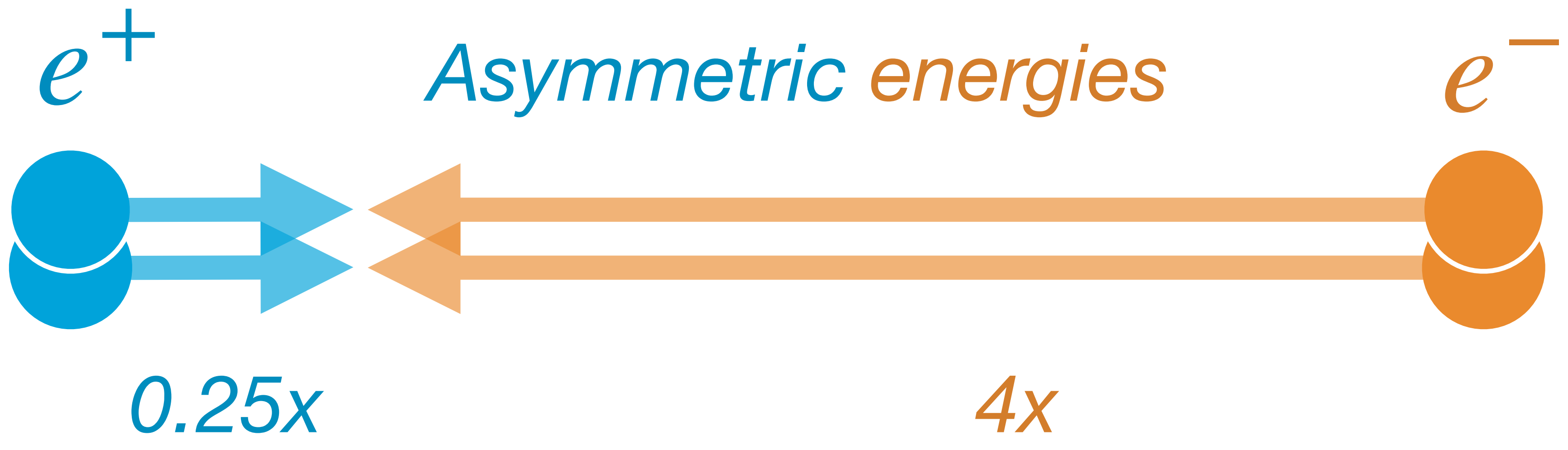
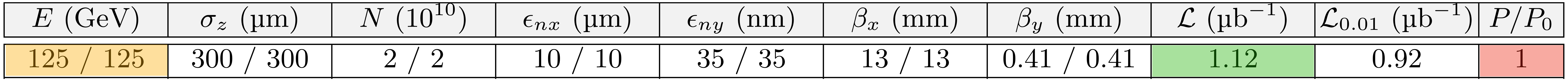
- A reasonable (but not necessarily optimized) choice is:
  - Electrons (from PWFA): **E_e = 500 GeV** (4x higher)
  - Positrons (from RF accelerator): **E_p = 31 GeV** (4x lower)
  - Boost: **γ = 2.13**
    (HERA had a boost of γ ≈ 3)



Simulating asymmetric e^+/e^- collisions

- GUINEA-PIG beam–beam simulations:



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ILC params

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- Asymmetric energies lead to a slight reduction in the geometric luminosity
- β functions are scaled accordingly to maintain the beam size at the IP

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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**

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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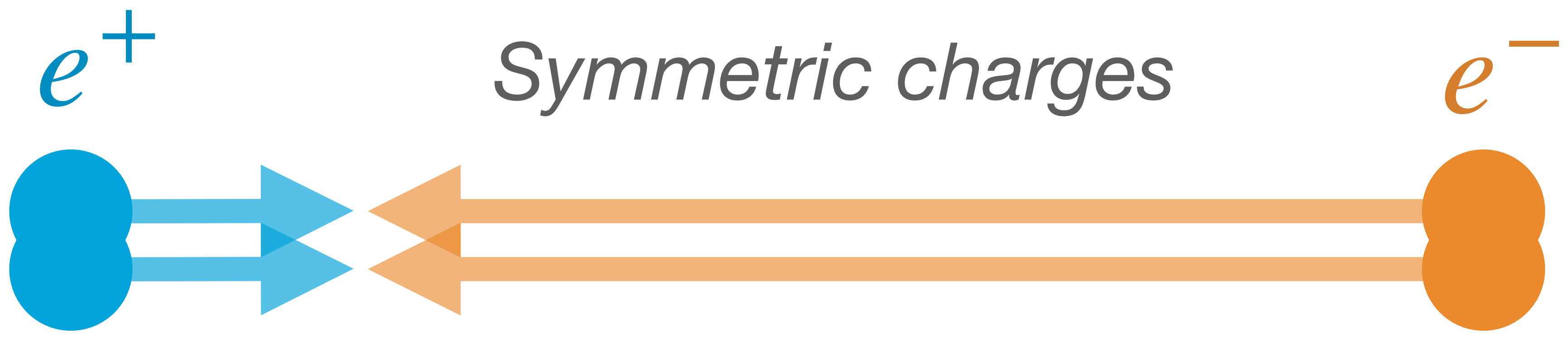

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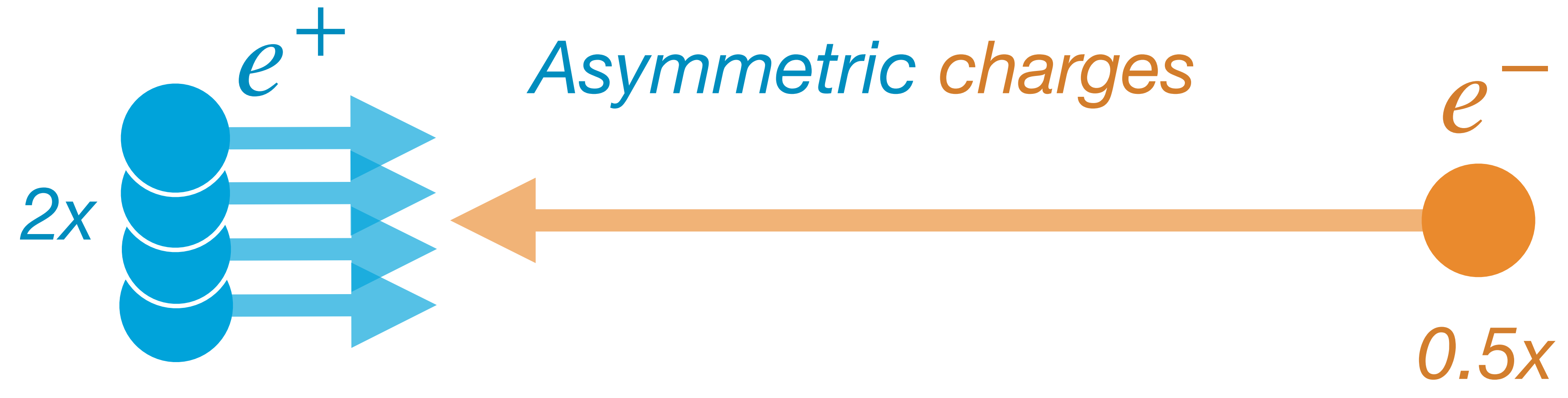

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- e^+ **must have smaller IP beta function (lower energy)**: 3.3/0.1 mm (CLIC-like ➞ *possible*)
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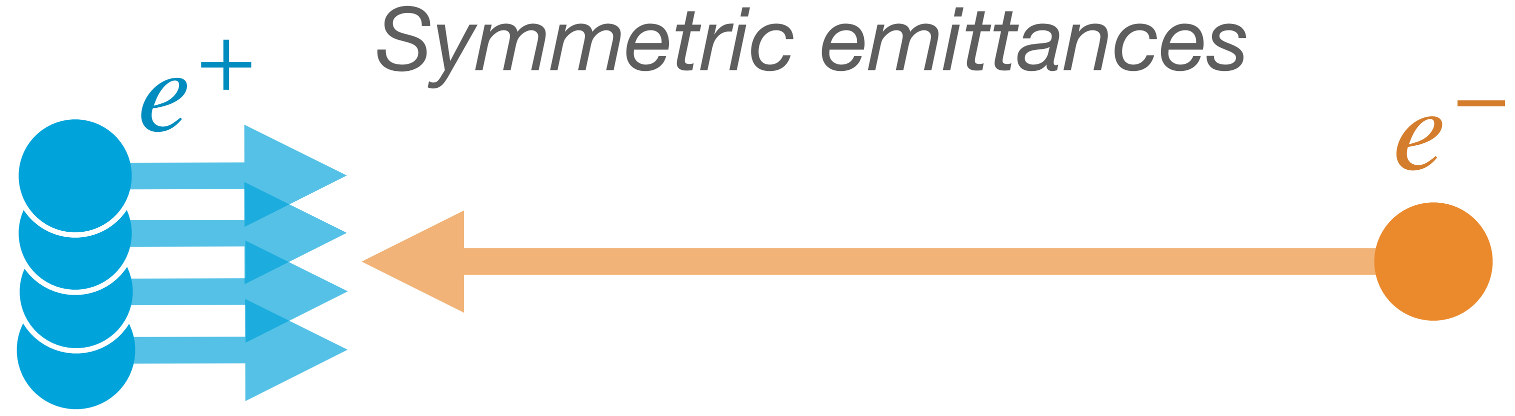

Symmetric emittances

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

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
31.3 / 500	75 / 75	4 / 1	10 / 10	35 / 35	3.3 / 52	0.10 / 1.6	1.04	0.60	1.25
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

- *Geometric* emittance scales as (energy)$^{-1}$ → can this help us?
- e^+ **must have smaller IP beta function (lower energy)**: 3.3/0.1 mm (CLIC-like → *possible*)
  - Conversely, electrons can have a larger IP beta function
- **Apply similar principle for the e^- (*normalised*) emittance**
  - Significantly reduces emittance requirements from PWFAs!

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Guiding strategy: **Minimise the required innovation**

- ***Risks multiply*** → need to keep the overall risk as low as possible

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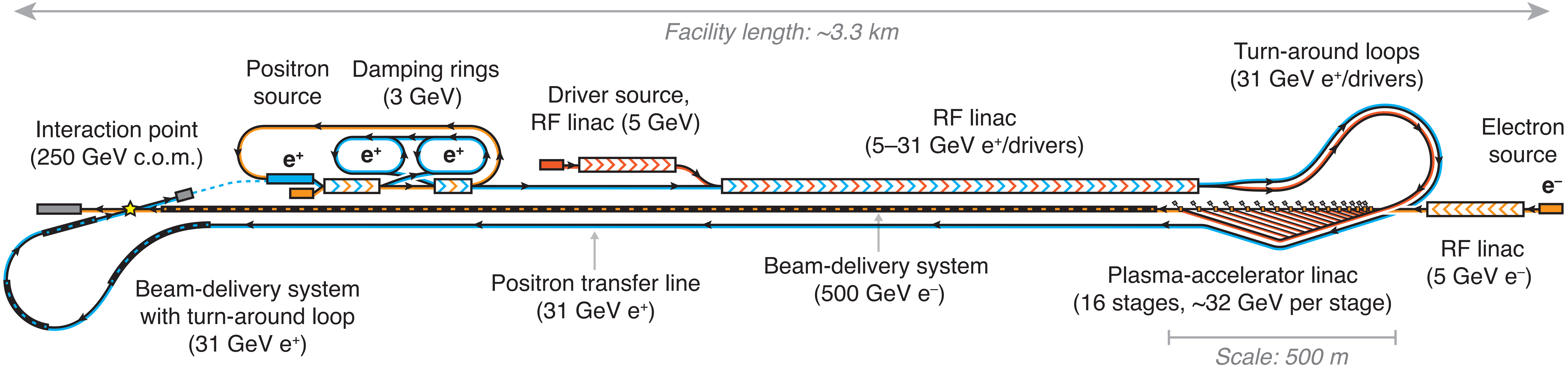
- ***Risks multiply*** → need to keep the overall risk as low as possible
  - There has been a great deal of technology development for colliders already
  - Focused on replacing the main linac with minimal (but not zero) changes elsewhere
  - Explicitly chose not to ‘plasma-ify’ everything (injectors, drivers, final focusing, etc.)

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory



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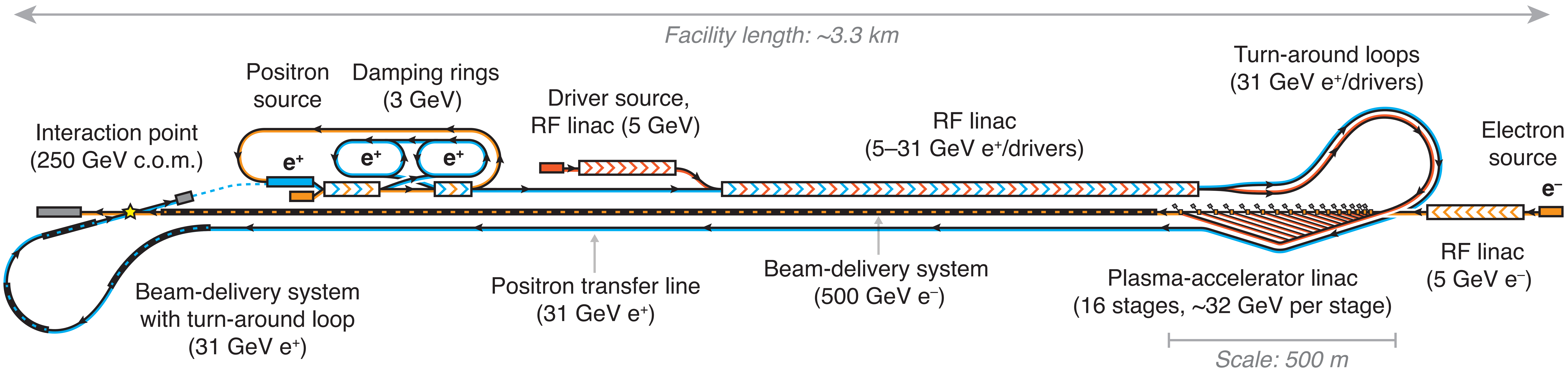

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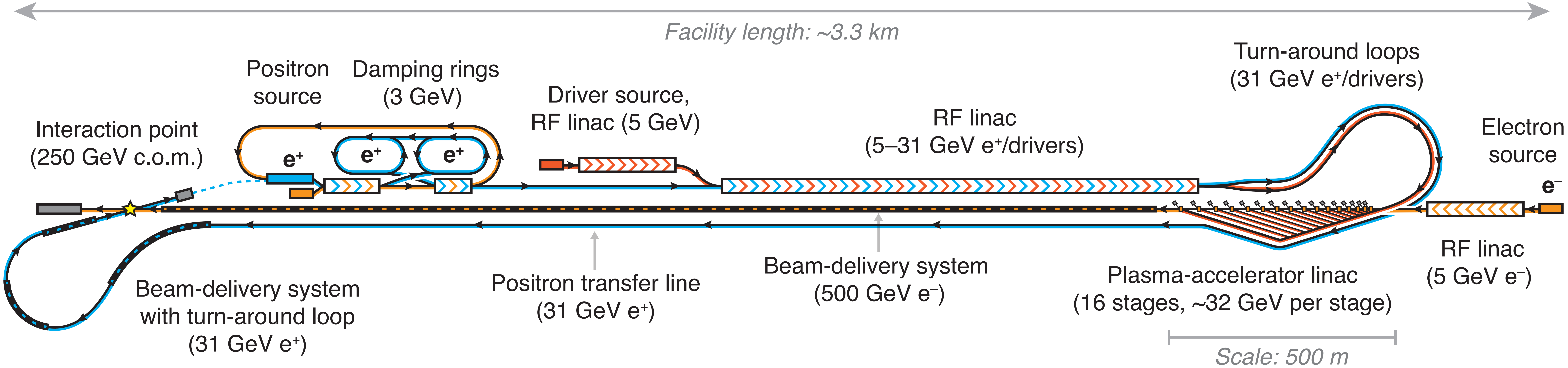

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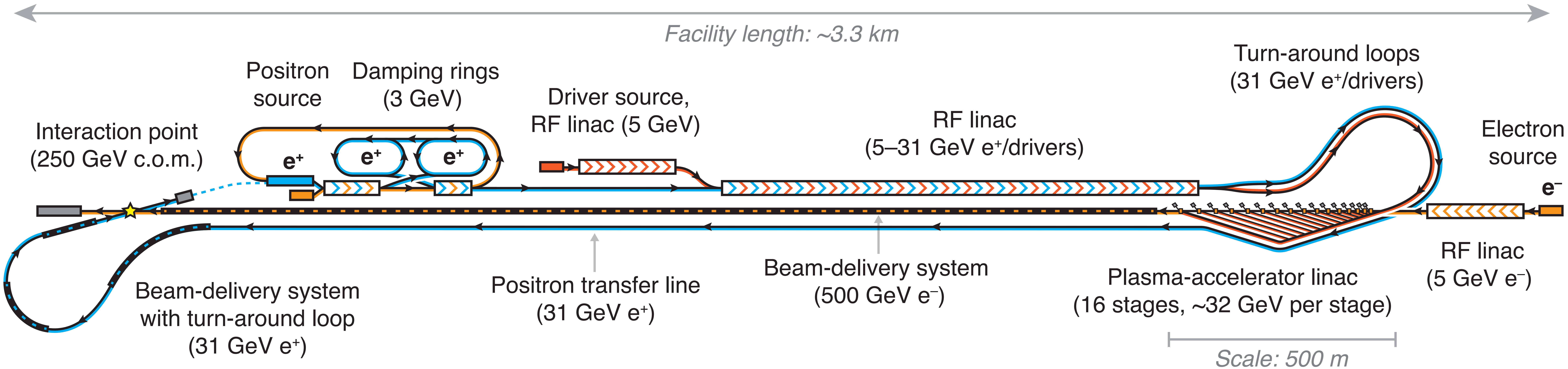

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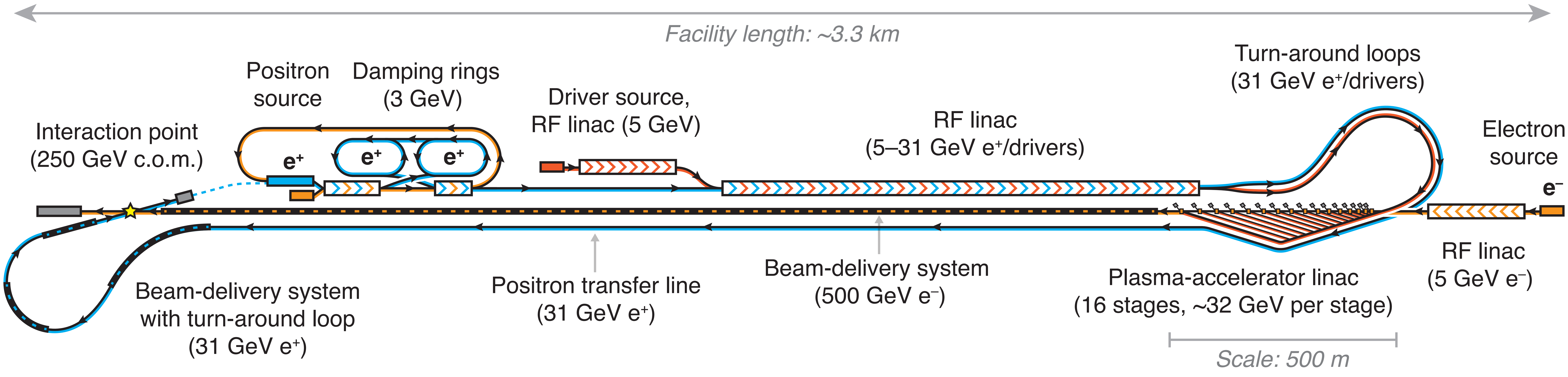

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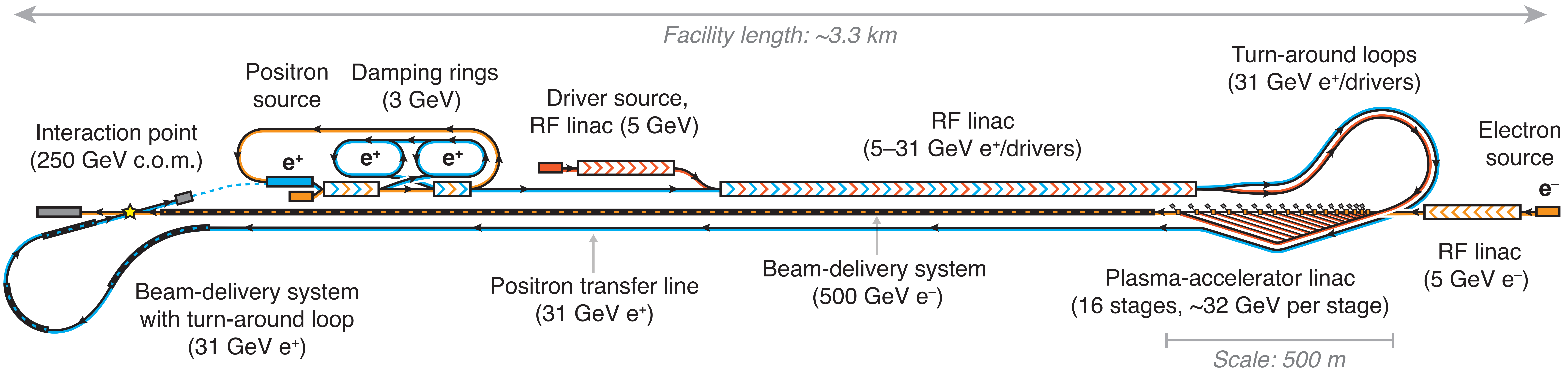

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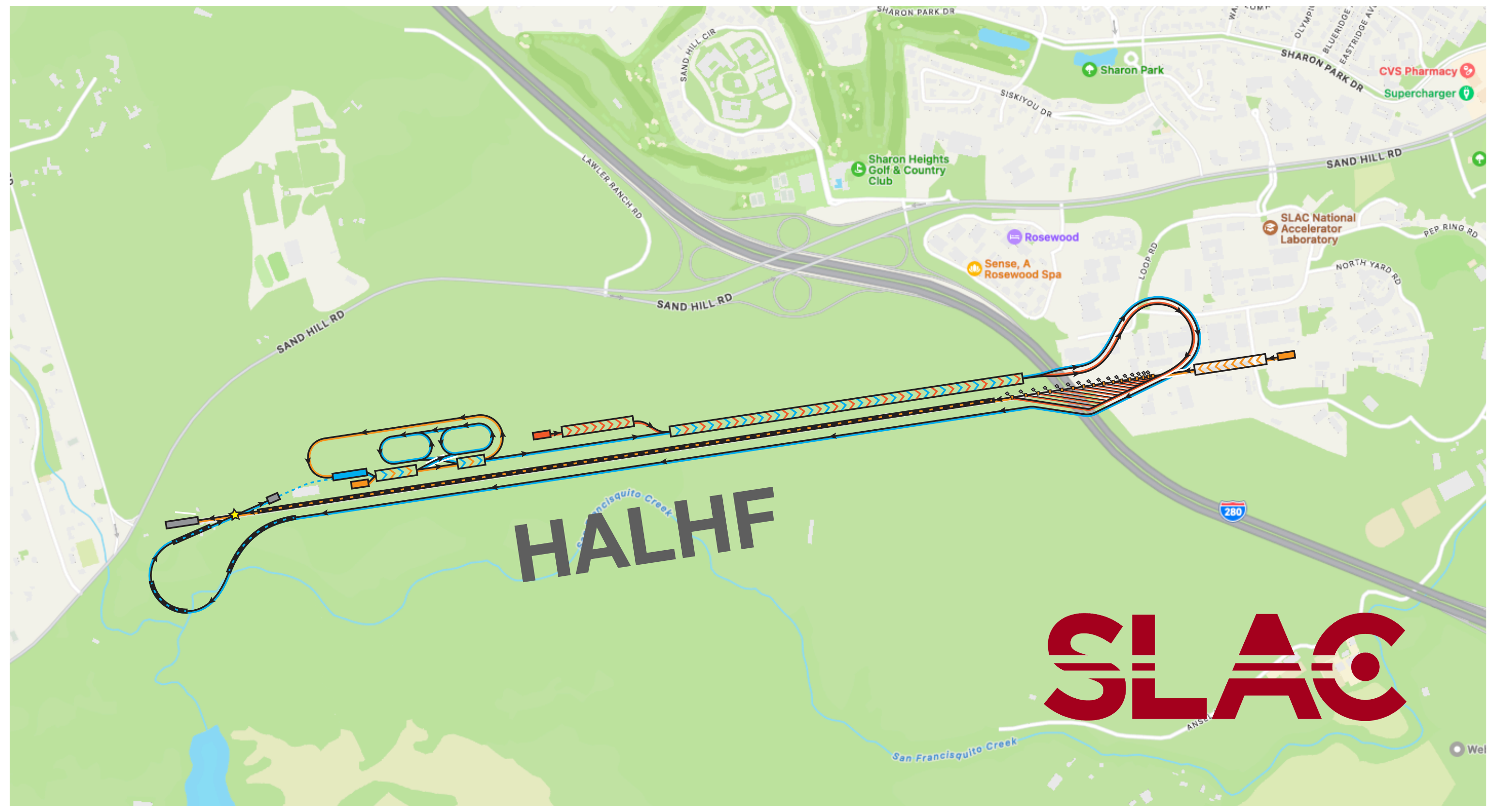
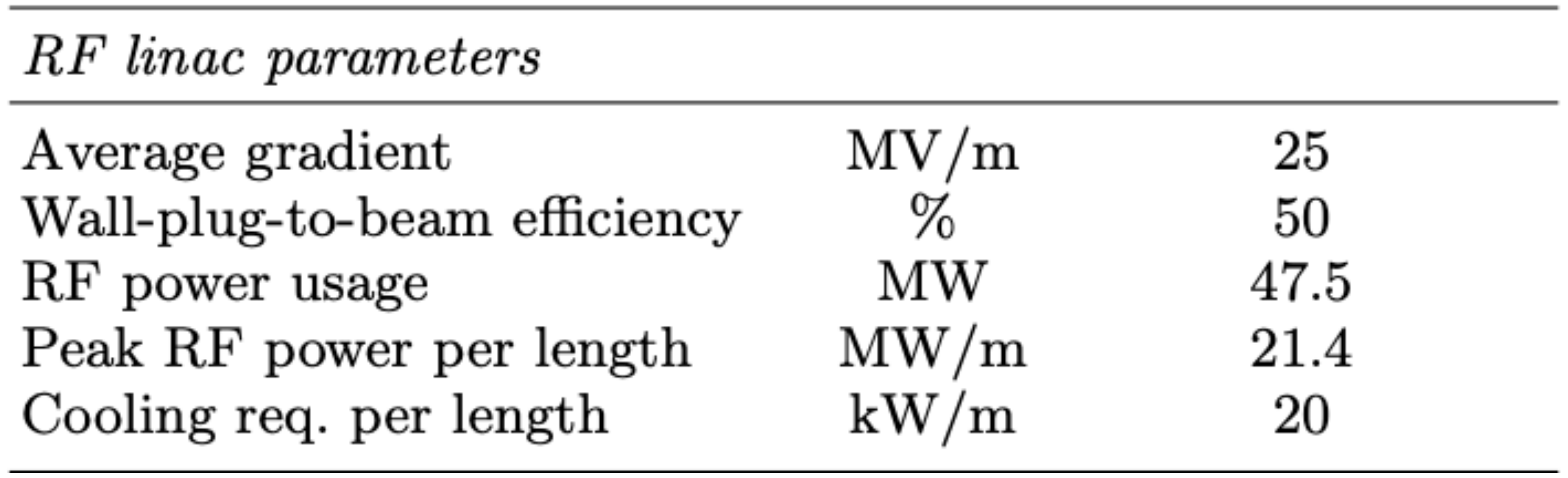
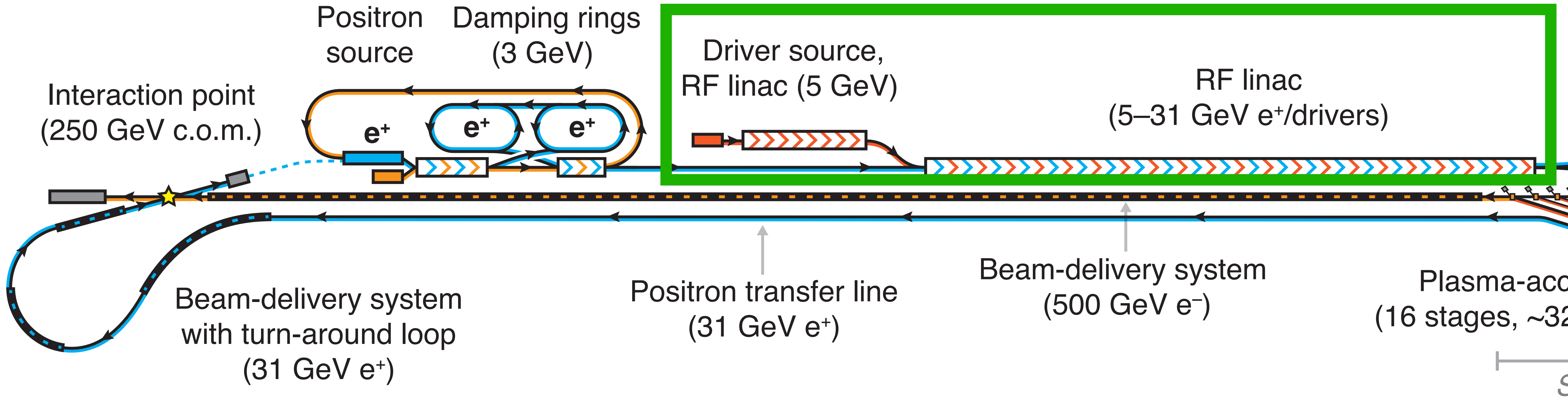


The foundation: **A dual-purpose RF linac**



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



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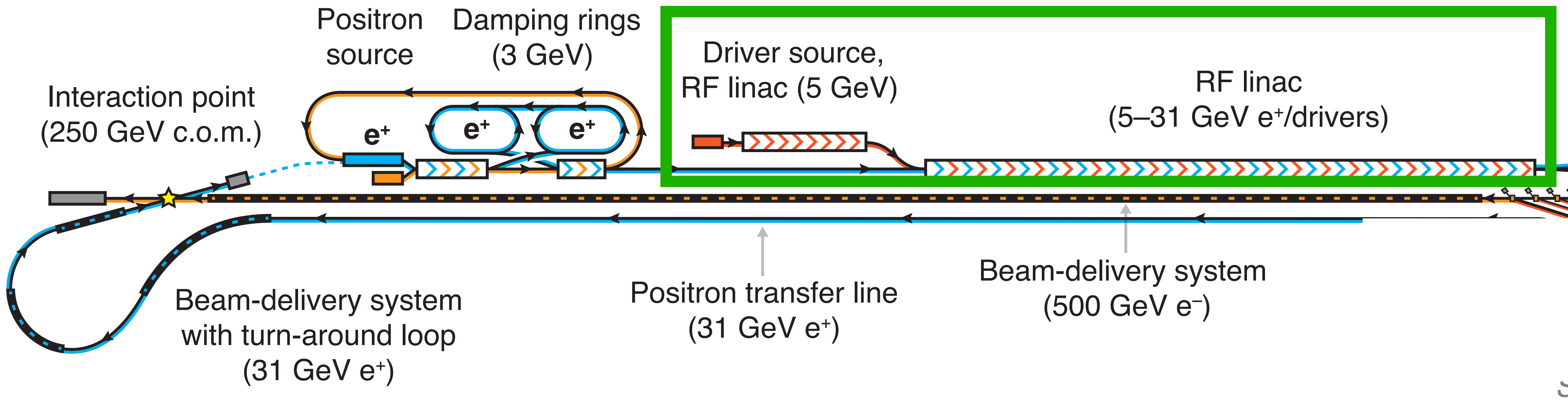

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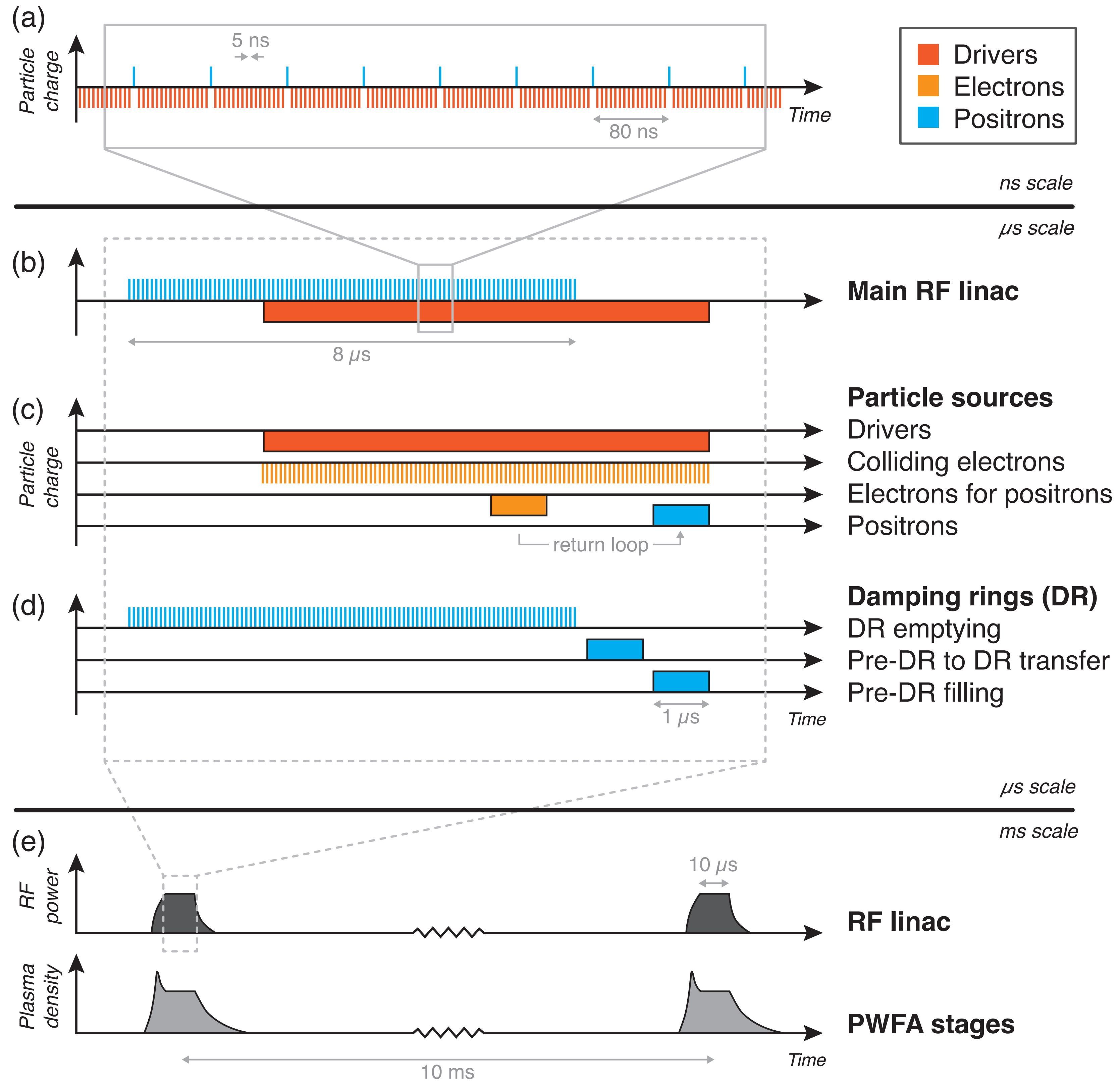
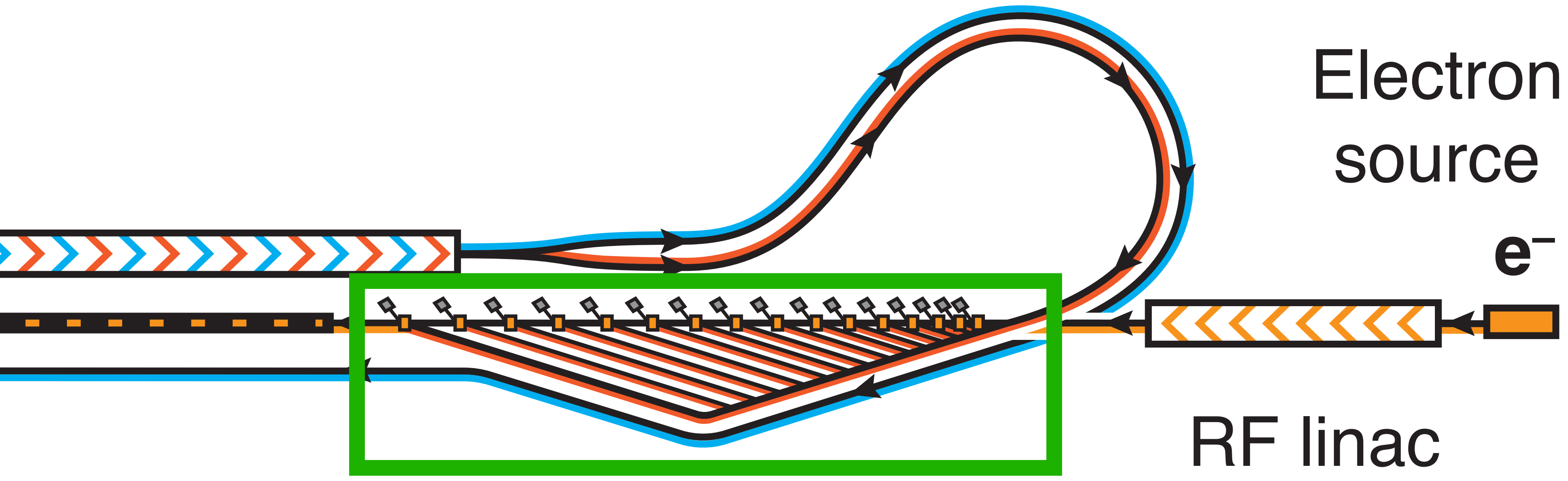
- ***Gradient***: 25 MV/m
- ***RF linac length***: ~1.25 km
- Assumes 50% efficient acceleration
- Bunch-train pattern must be compatible with PWFA stages ➞ ***active research topic at Oxford***:
  - Normal-conducting RF? Burst-mode (100 bunches @ 100 Hz)?
  - Super-conducting RF? Continuous wave (10 kHz)?



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

> ***Length***: 16 PWFA stages (5-m long): ~400 m total length

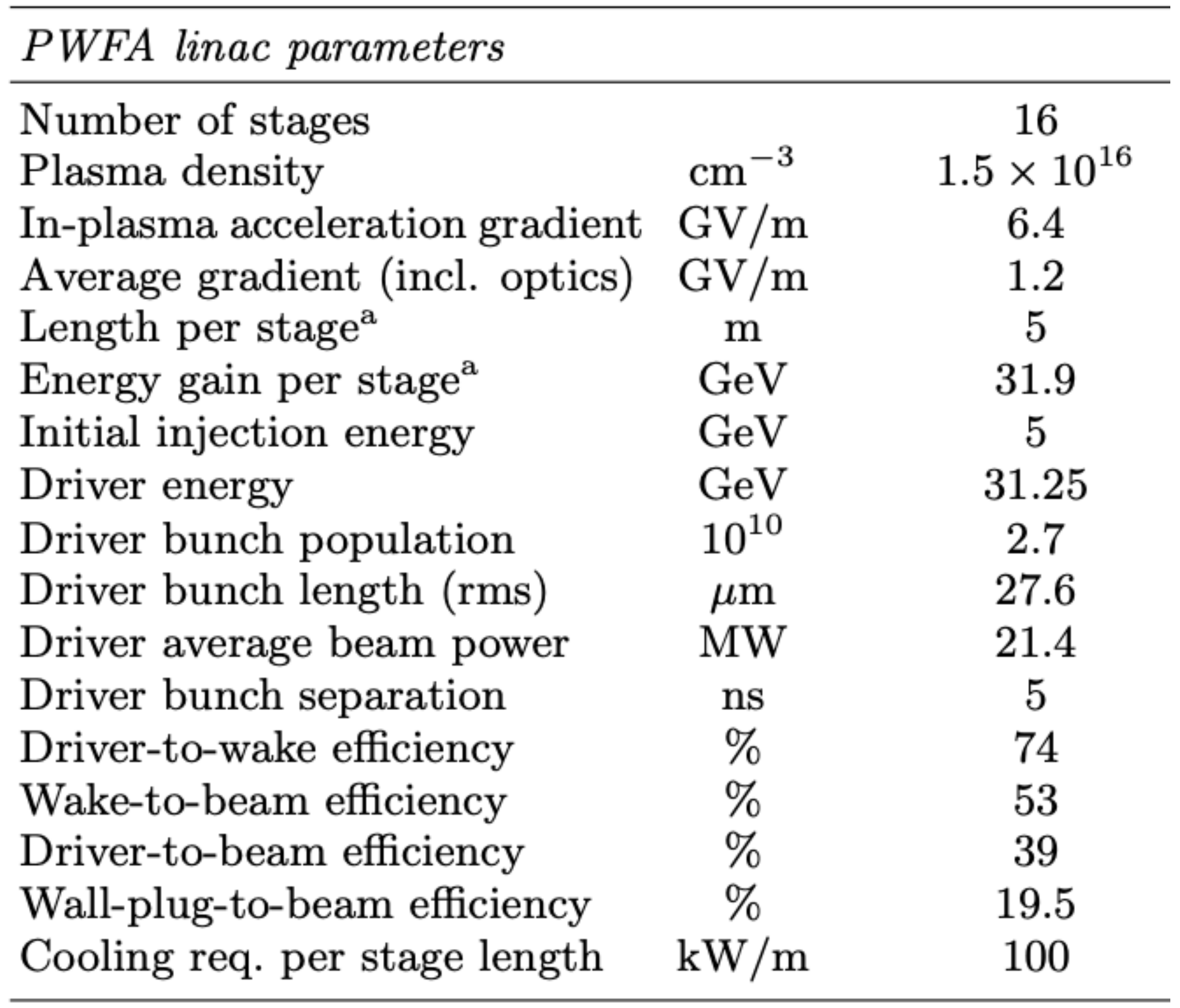


Turn-around loops
(31 GeV e⁺/drivers)

Electron
source

Plasma-accelerator linac
(16 stages, ~32 GeV per stage)

RF linac
(5 GeV e⁻)



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

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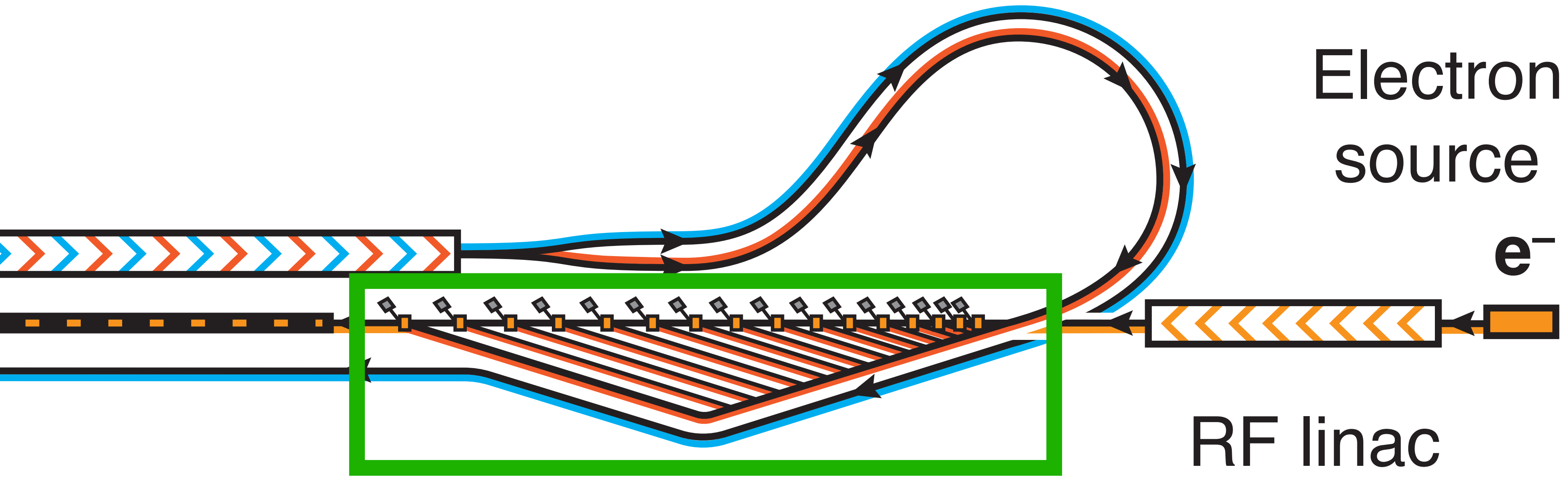
- **_Efficiency_**: 38% = 72% (wake input) x 53% (wake extraction)



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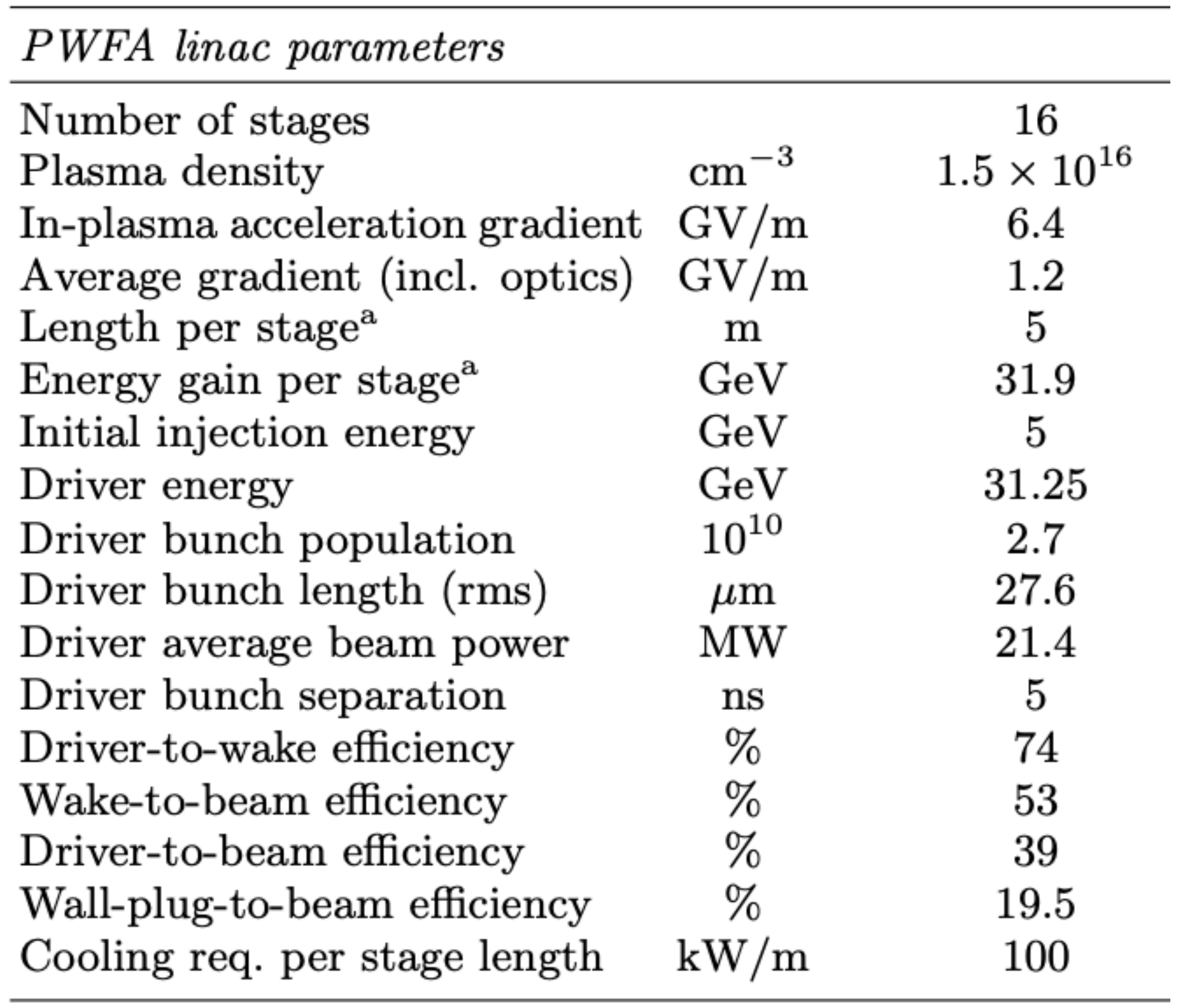

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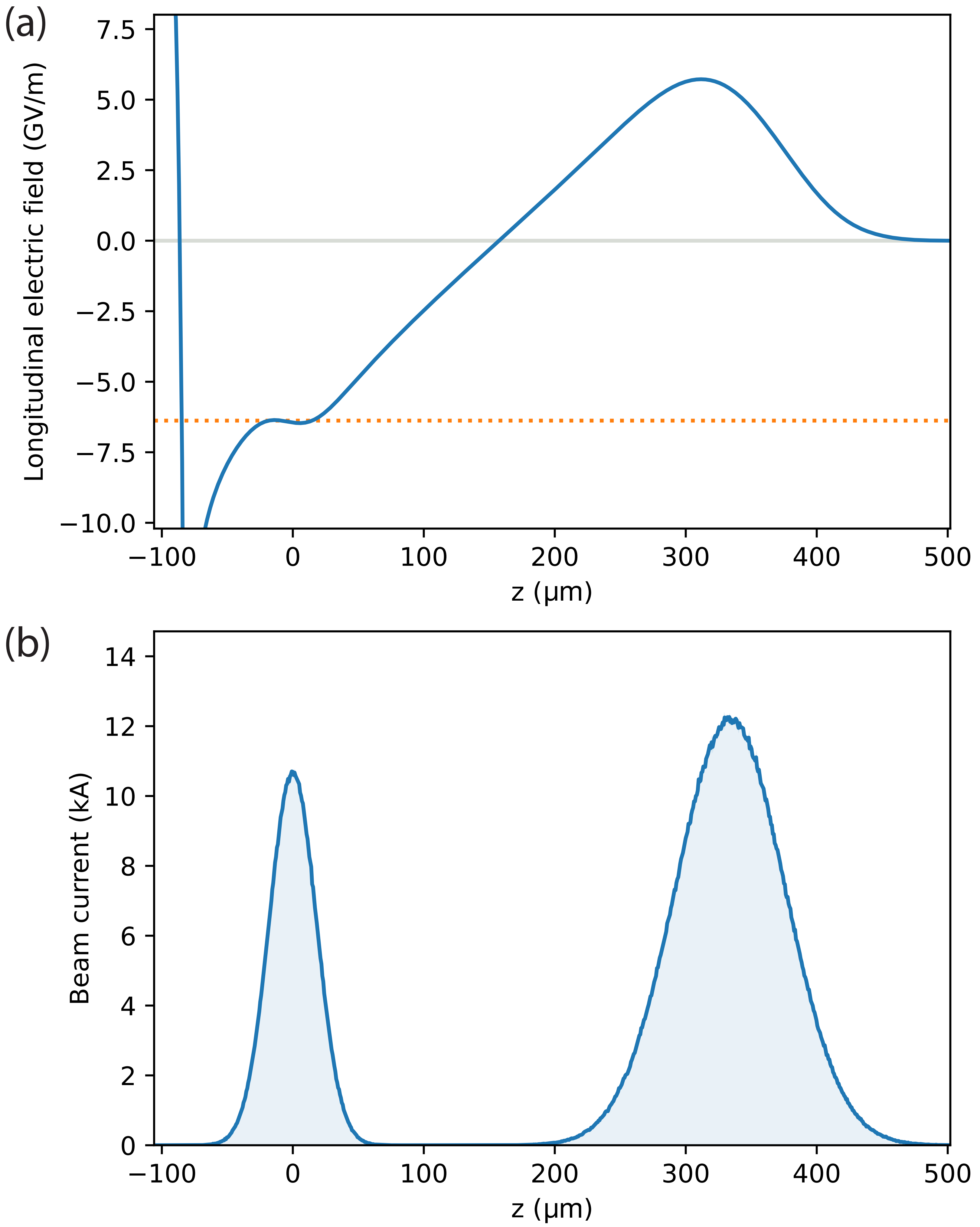

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Plasma density: 7 x 10^{15} cm^{-3}
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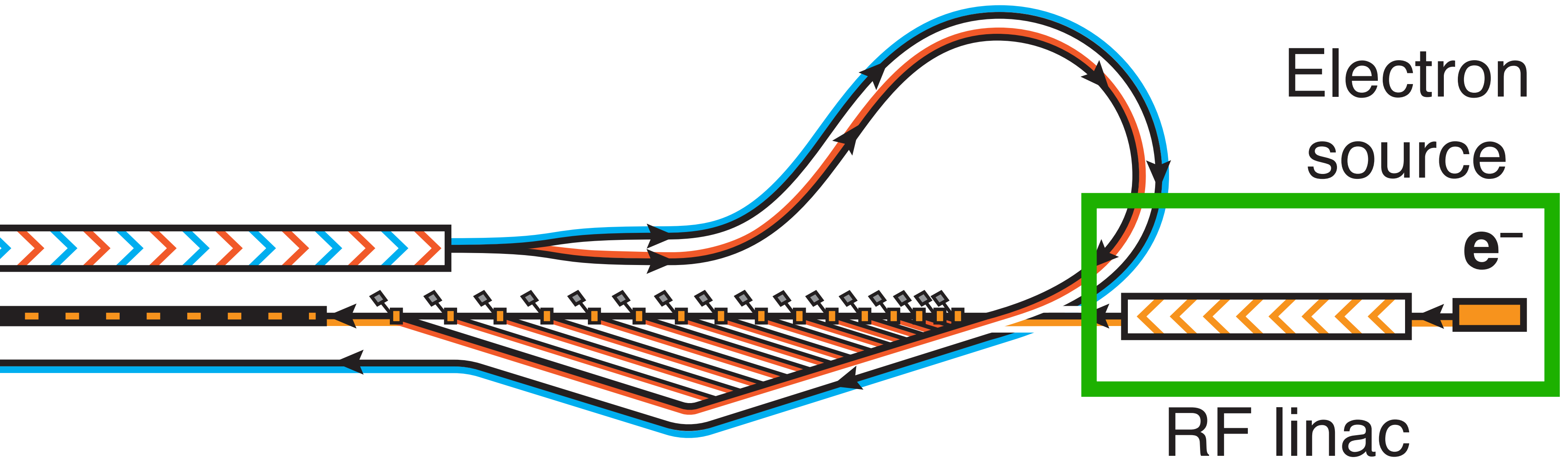

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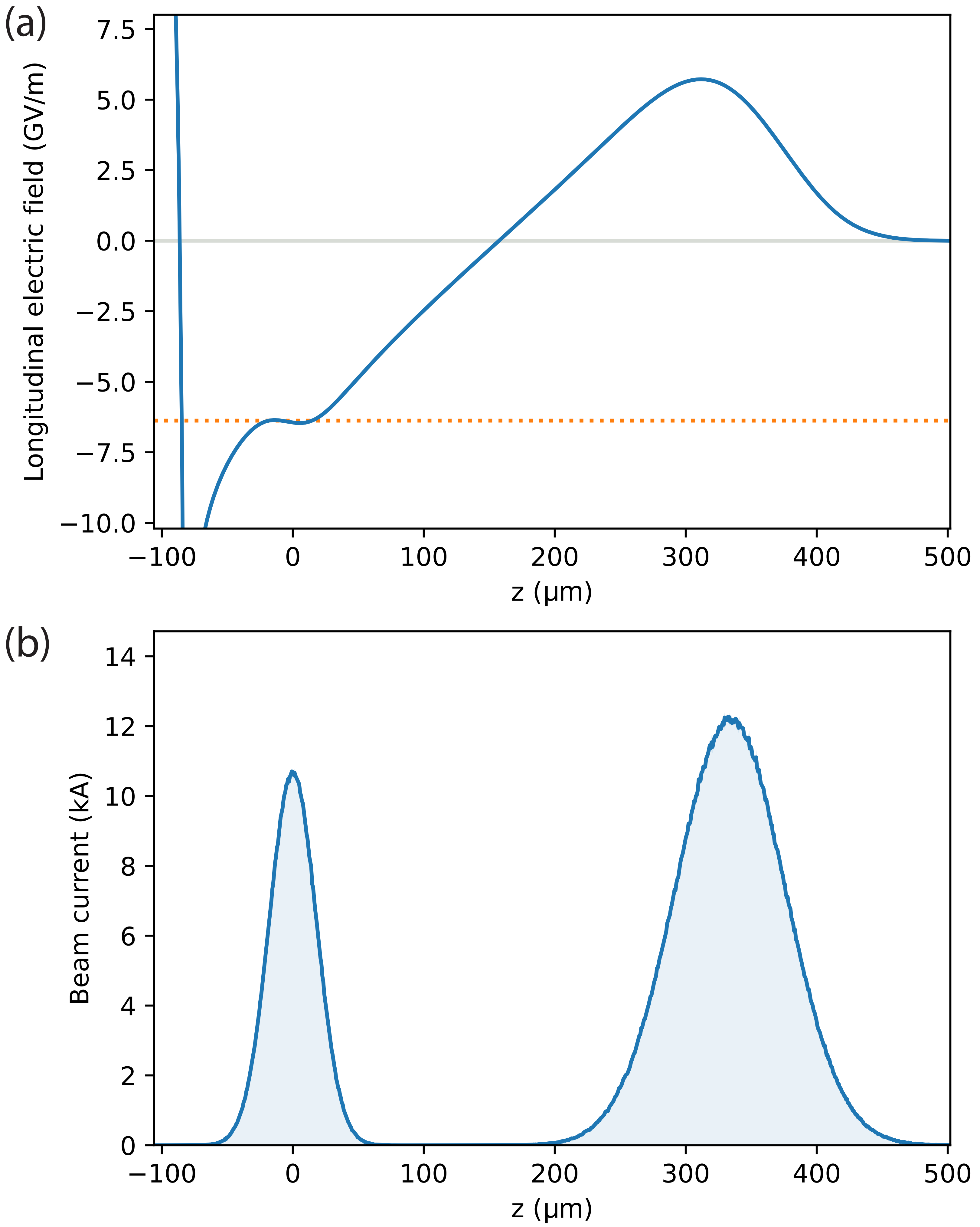

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Rough cost estimates for HALHF

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  - European accounting (2022 $): **~$1.9B** (**~1/4 of ILC TDR cost** @ 250 GeV)
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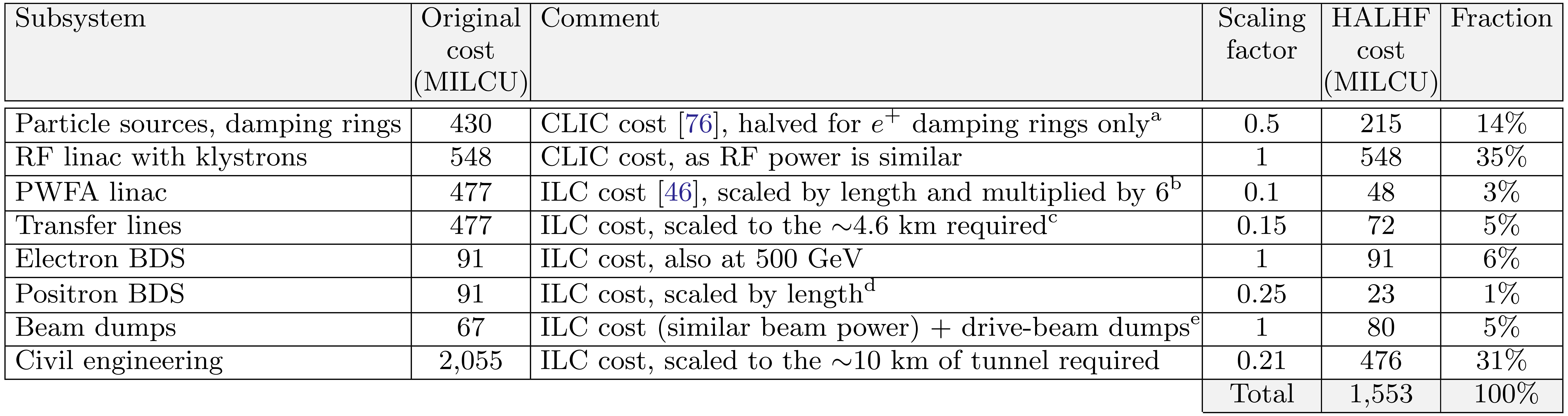

Subsystem	Original cost (MILCU)	Comment	Scaling factor	HALHF cost (MILCU)	Fraction
Particle sources, damping rings	430	CLIC cost [76], halved for e^+ damping rings only[a]	0.5	215	14%
RF linac with klystrons	548	CLIC cost, as RF power is similar	1	548	35%
PWFA linac	477	ILC cost [46], scaled by length 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%

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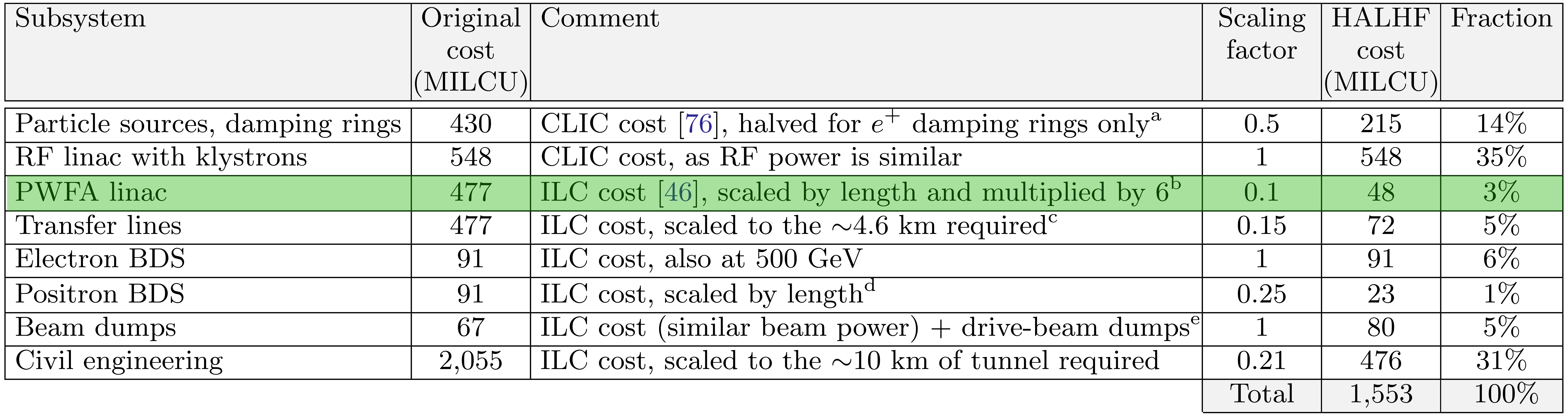

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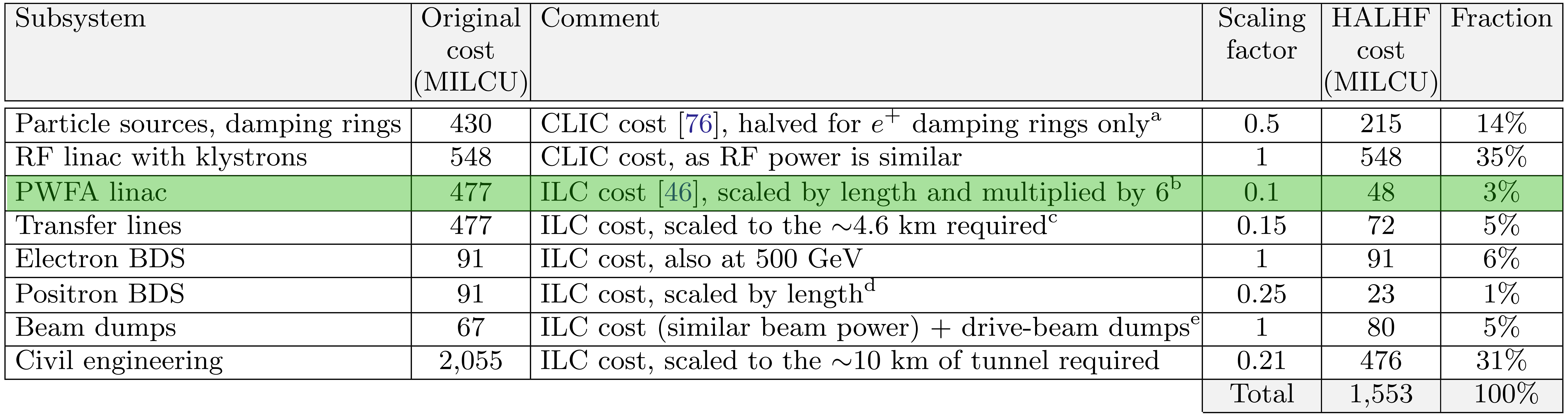

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- Estimated **power usage is ~100 MW** (similar to ILC and CLIC):
  - 21 MW beam power + 27 MW losses + 2×10 MW damping rings + 50% for cooling/etc.

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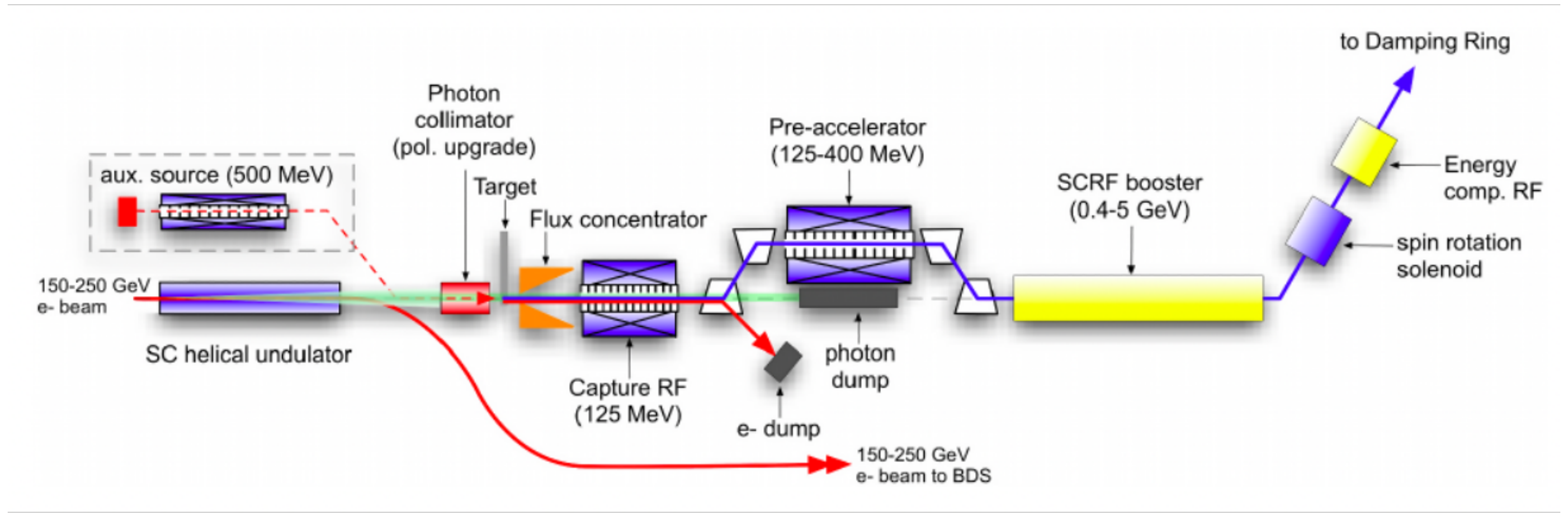
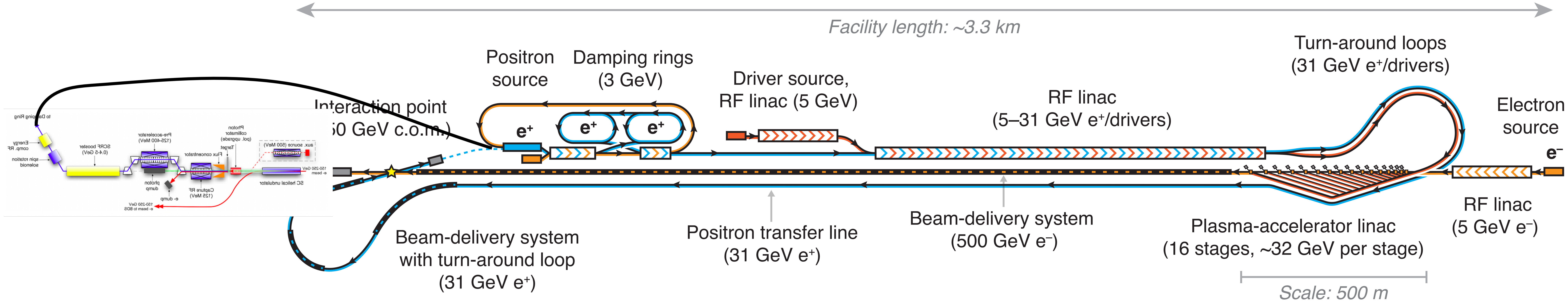
Upgrades: **Polarised positrons**

- Produce e+ polarisation via ILC-like scheme:
  - ***Pro***: minimally disrupted electron beam
  - ***Pro***: ideas exist for E(e-) 500 GeV
  - ***Con***: wiggler probably longer and more expensive
- Cost 5–10% of original cost (+ ~100M€)

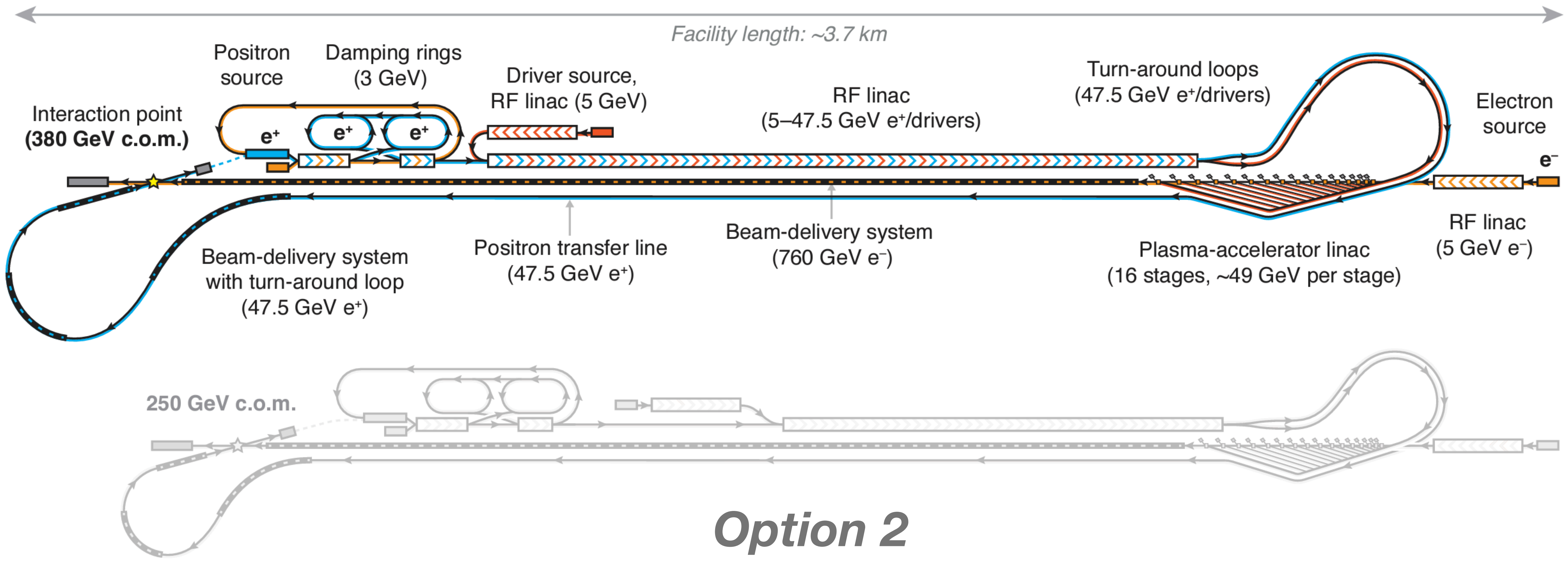




Source: Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

Upgrades: **380 GeV centre of mass**

- Operation at the t–tbar threshold (346 GeV) typically motivates a c.o.m. up to 380 GeV
  - … which is in fact the minimum energy proposed for CLIC
- Two options:
  - 31 GeV positrons / **1165 GeV electrons** (more plasma stages, higher γ, lower efficiency)
    ➞ +1 km PWFA linac
  - **47.5 GeV positrons** / **760 GeV electrons** (same # of [longer] stages, same γ as original)
    ➞ +130 m PWFA linac
- Second option preferred
  - Increased length ~10%
  - Added cost ~10%
  - ~25% more power overall



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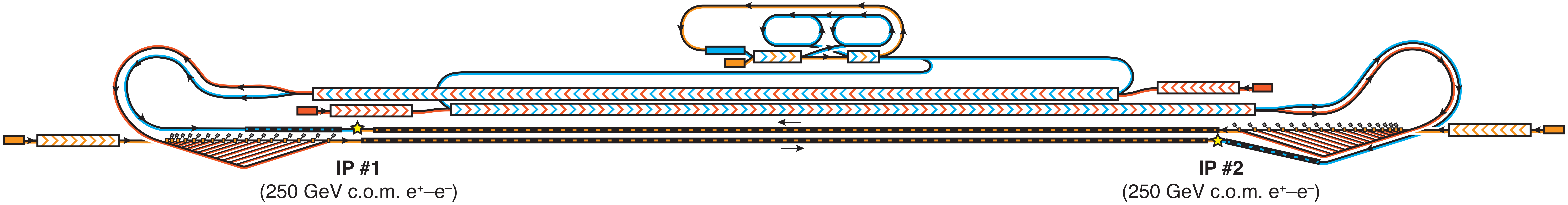

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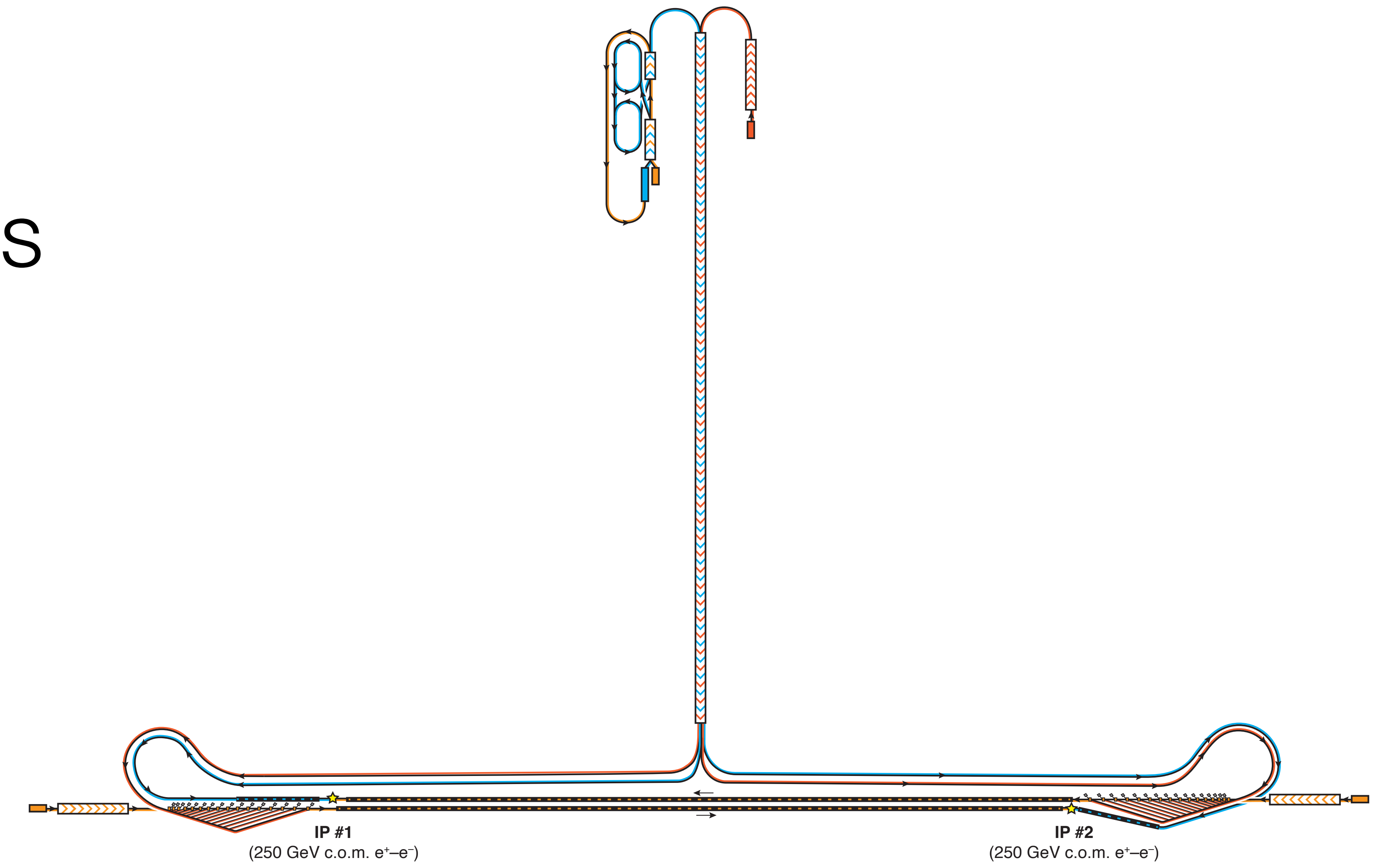

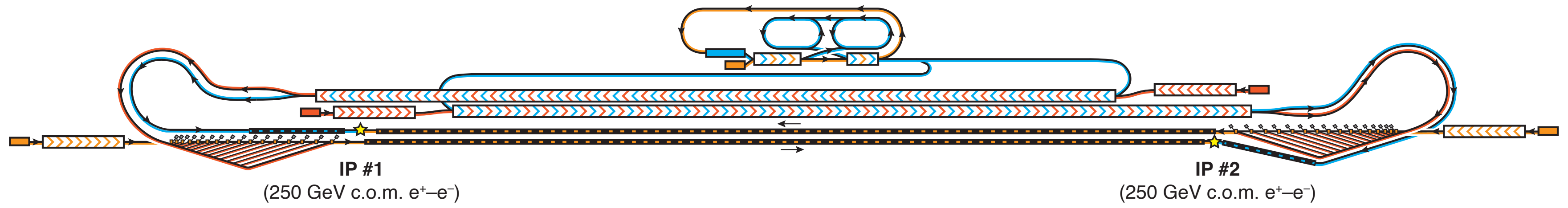

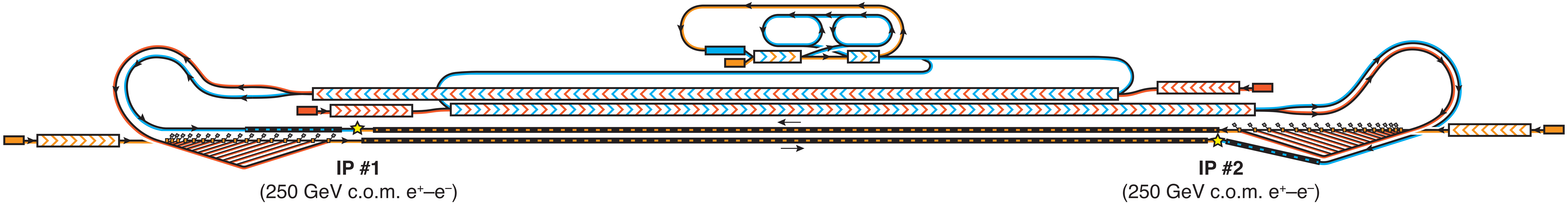

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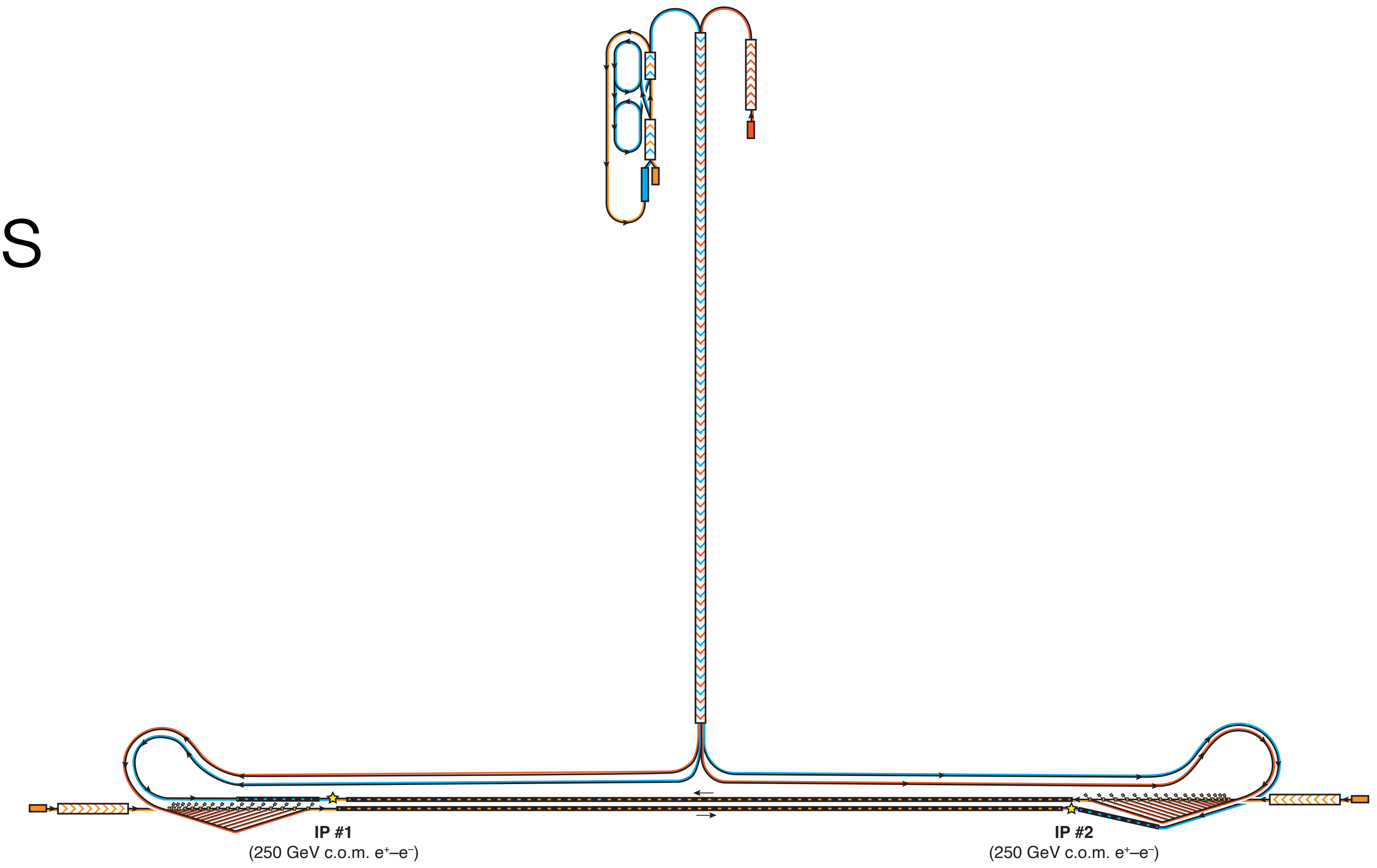
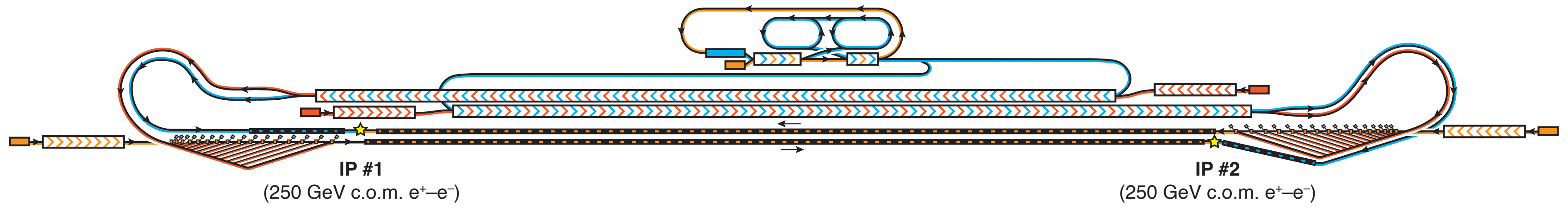
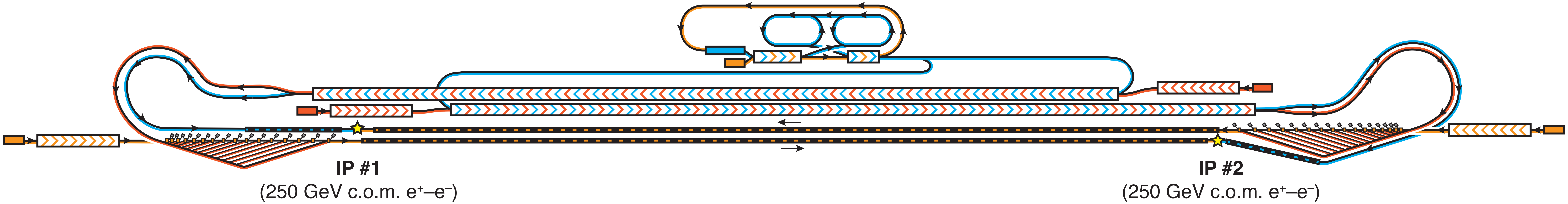
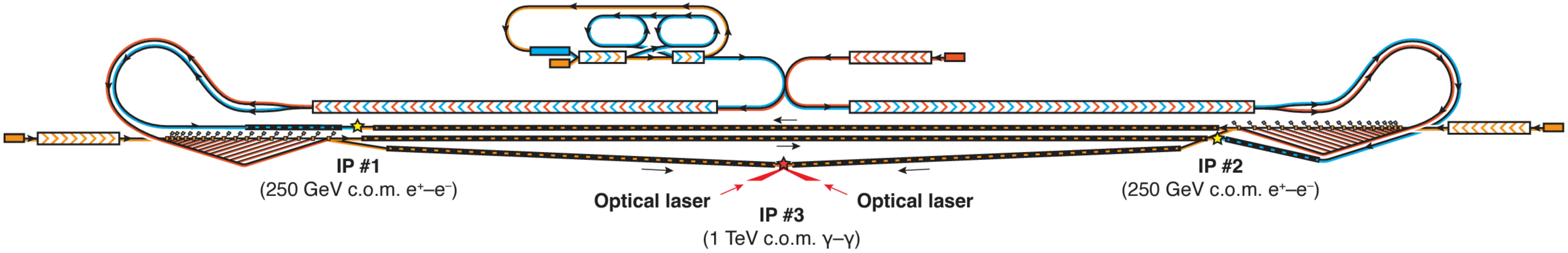
- May be important politically (systematics, 2x physicists)







Upgrade: **TeV γ–γ collider** *(optical laser version)*



- ***Collide 500 GeV γ beams*** *(up to 1 TeV c.o.m. with original HALHF scheme)*

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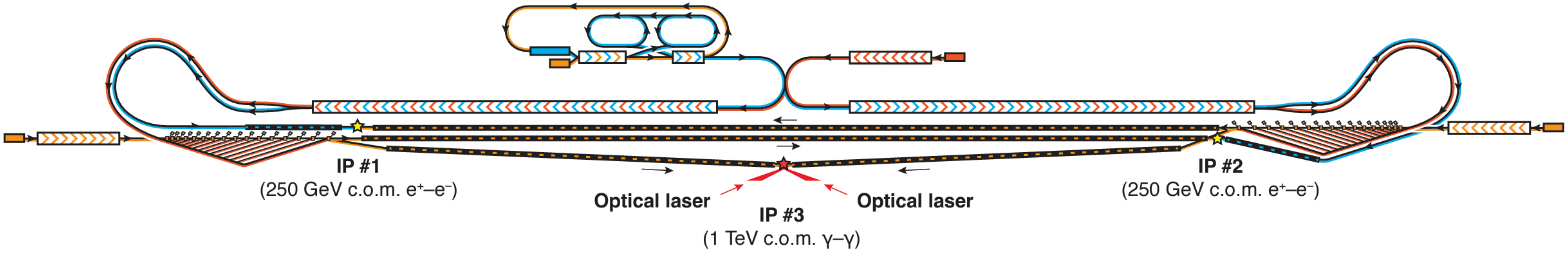

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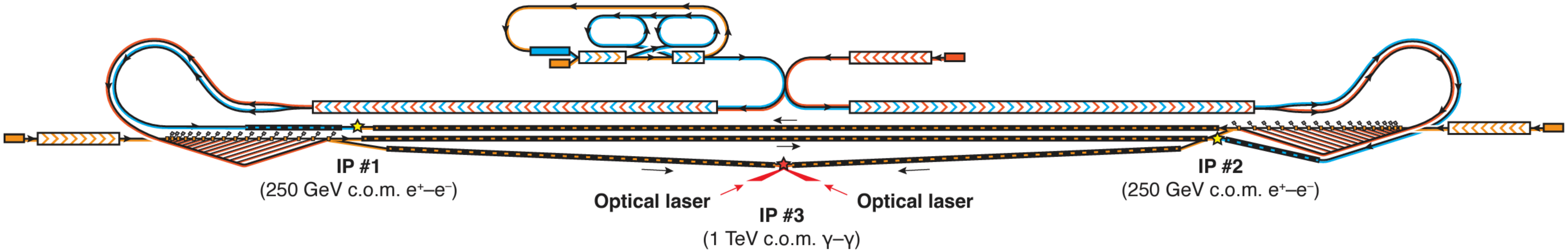
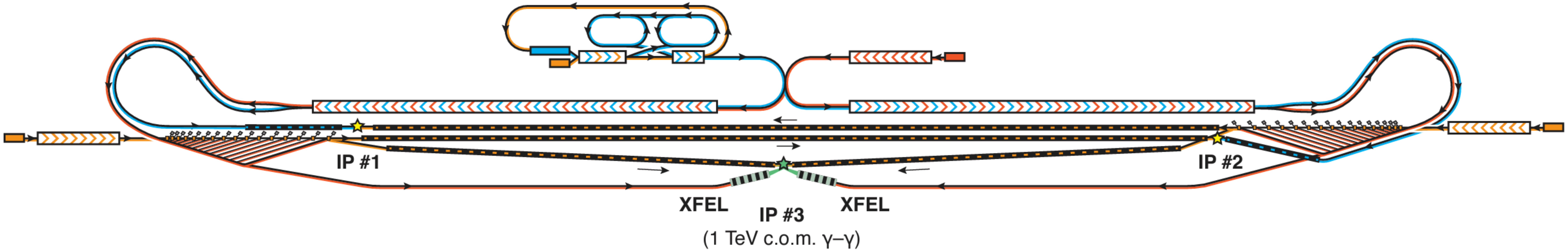
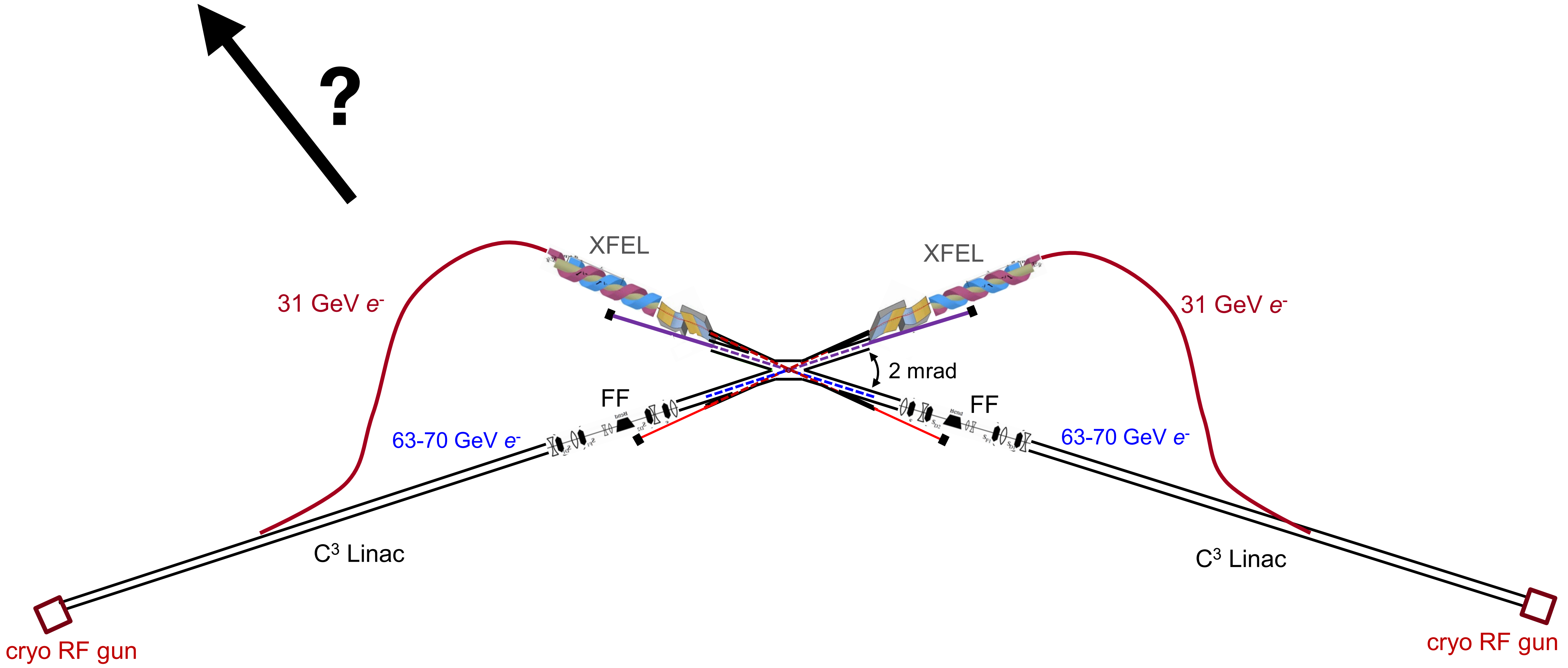


- ***Collide 500 GeV γ beams*** (*up to 1 TeV c.o.m. with original HALHF scheme*)
- γ produced from Compton backscattering off lasers ➞ technology does not yet exist
- Several additional challenges:
  - Requires lower emittances (*but can have round beams*)
  - Requires shorter BDS
  - Laser technology (*very high power*) currently does not exist

Upgrade: **TeV γ–γ collider** *(XFEL version)*



- New concept from C^3/SLAC colleagues
  - Use X-rays instead of optical laser



XCC: An X-ray FEL-based γγ Collider Higgs Factory
Barklow et al., arXiv:2203.08484 (2022)

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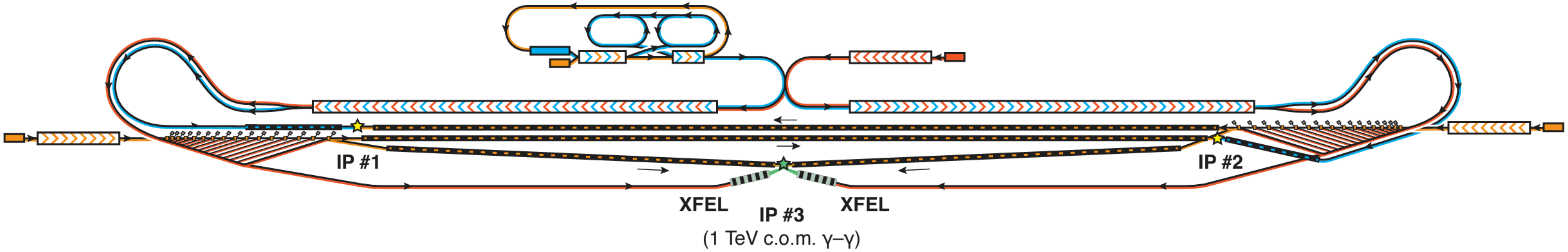

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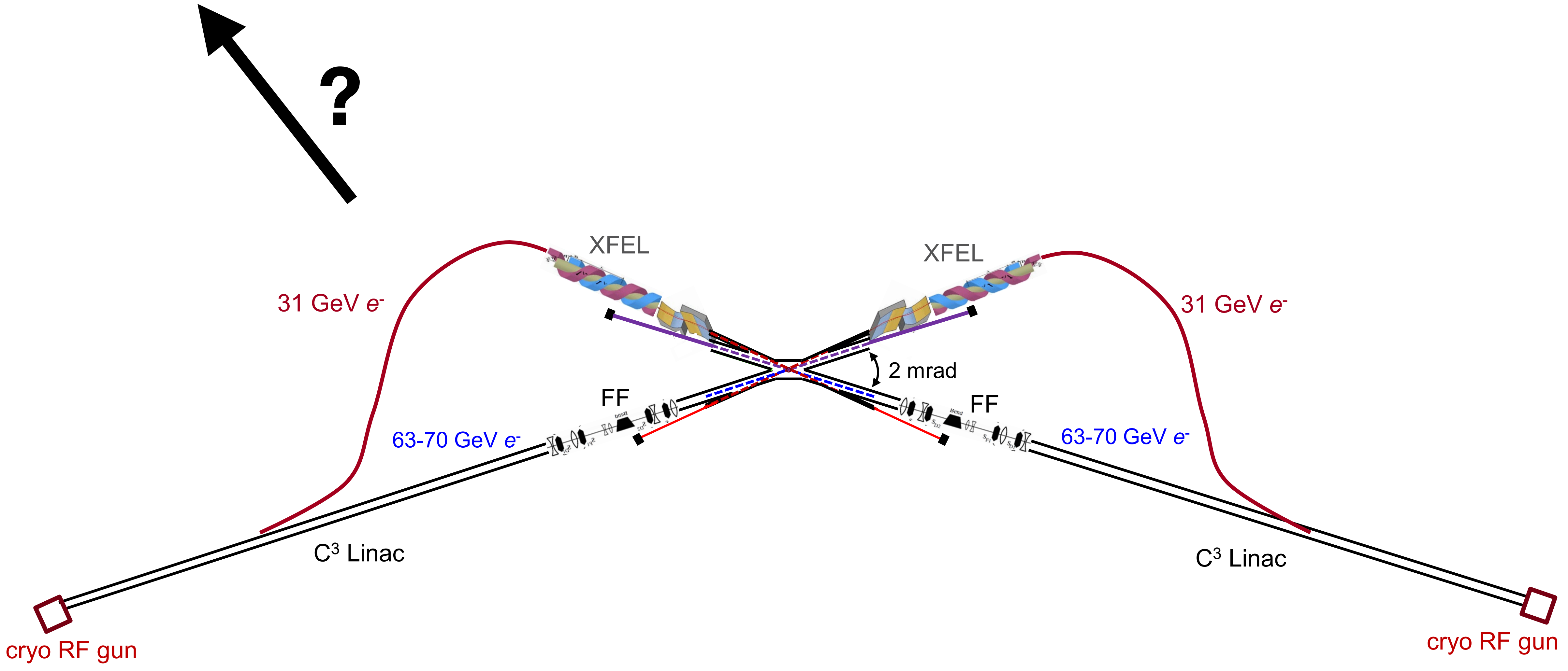

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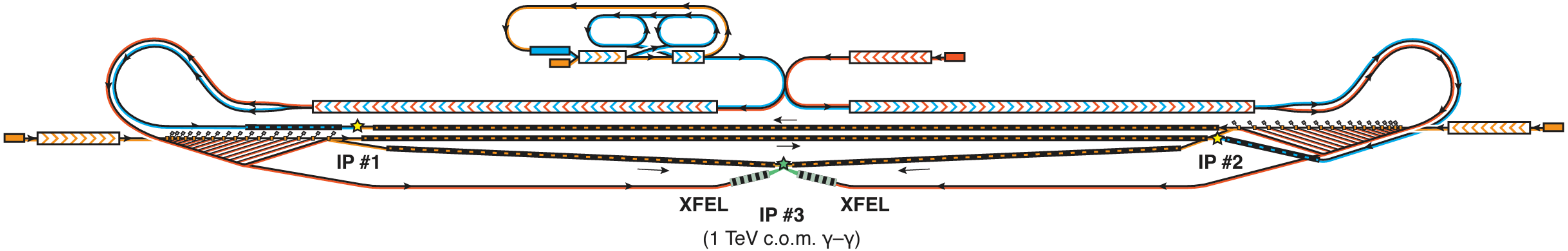

- New concept from C³/SLAC colleagues
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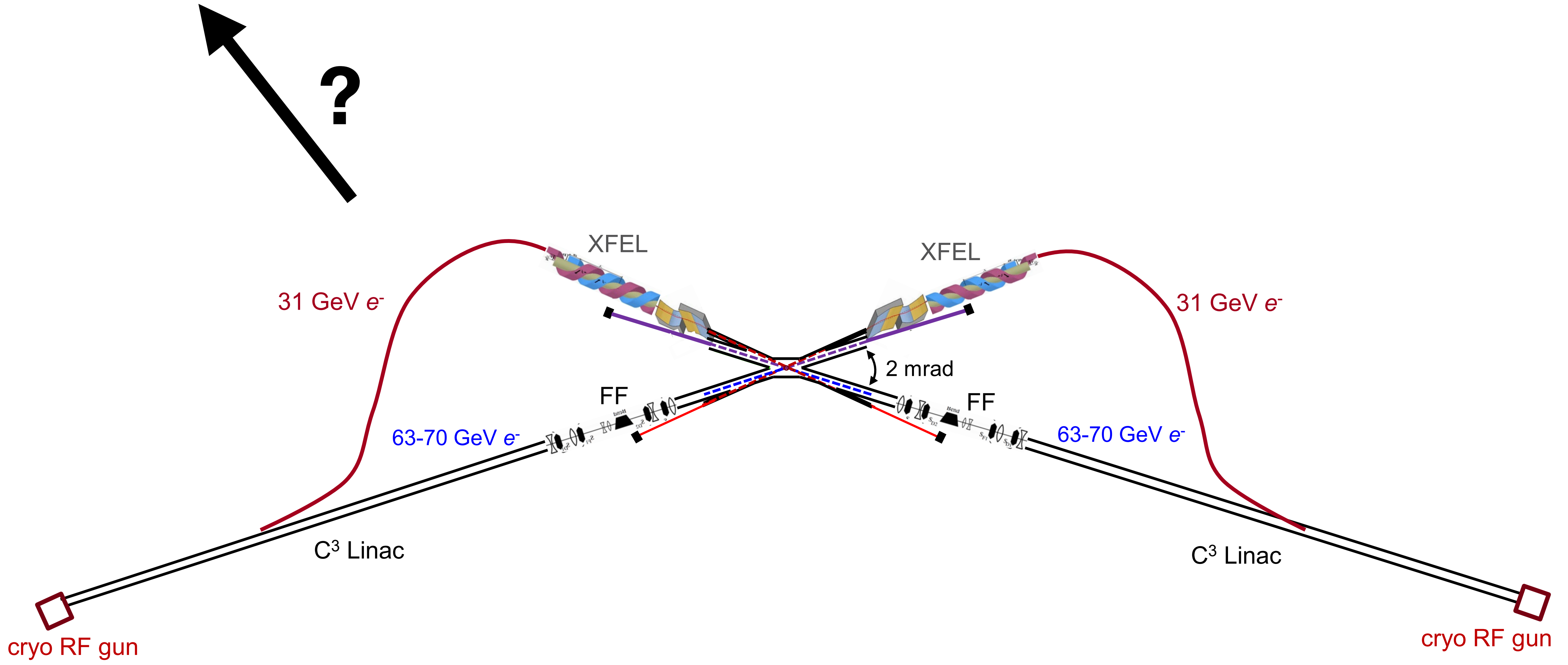
- Somewhat advanced but has benefits: *we already have the high-power laser source*
- Would be the most powerful XFEL ever: *photon scientists may wish to collaborate*



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Outline

- > Motivation
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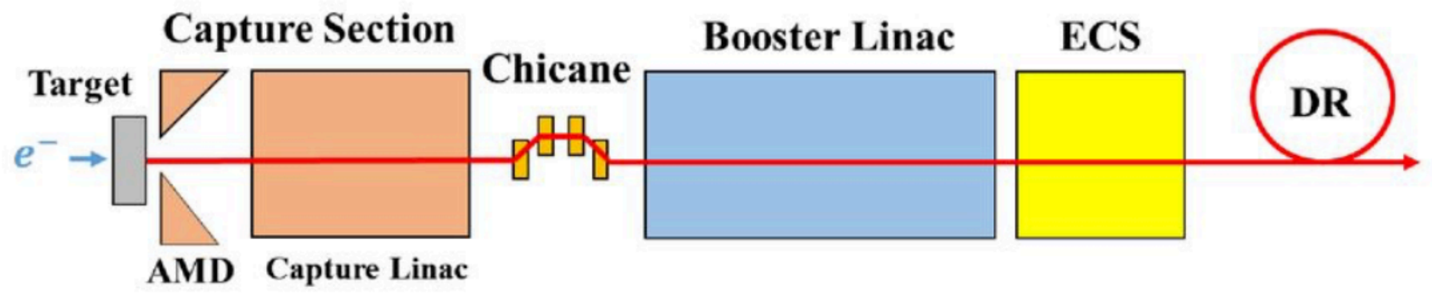
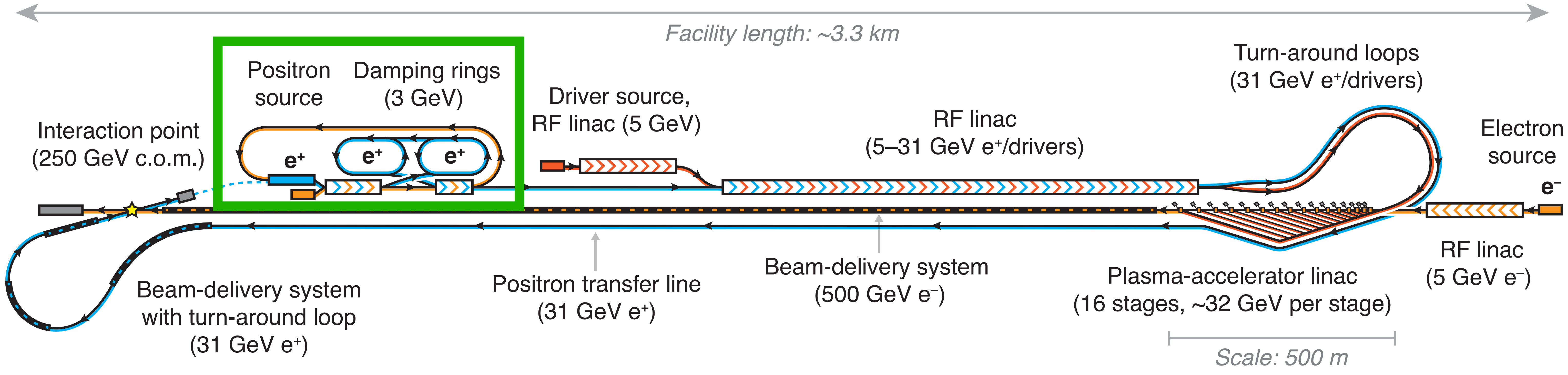
- > Timeline & Staging
- > Conclusions

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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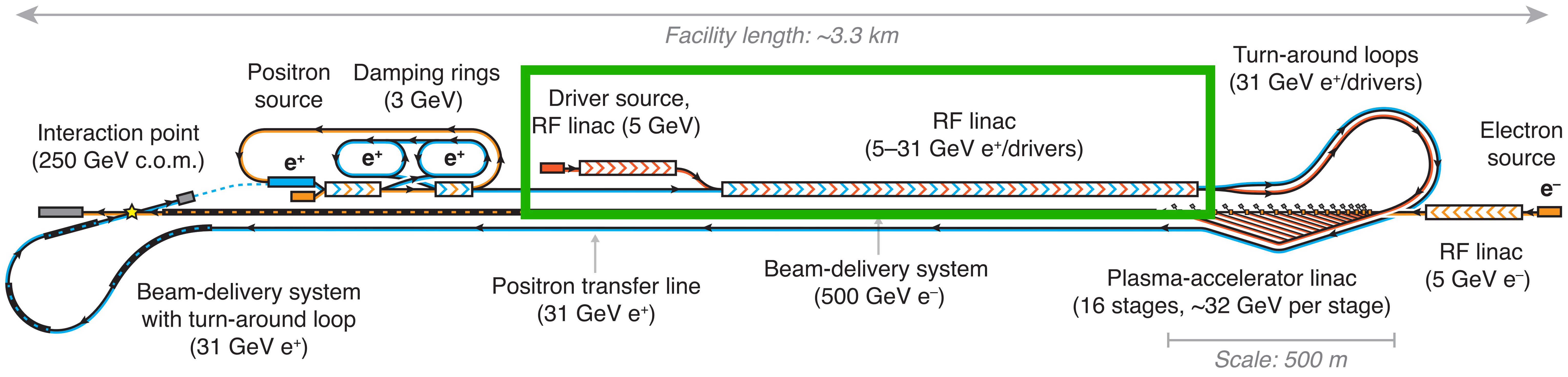

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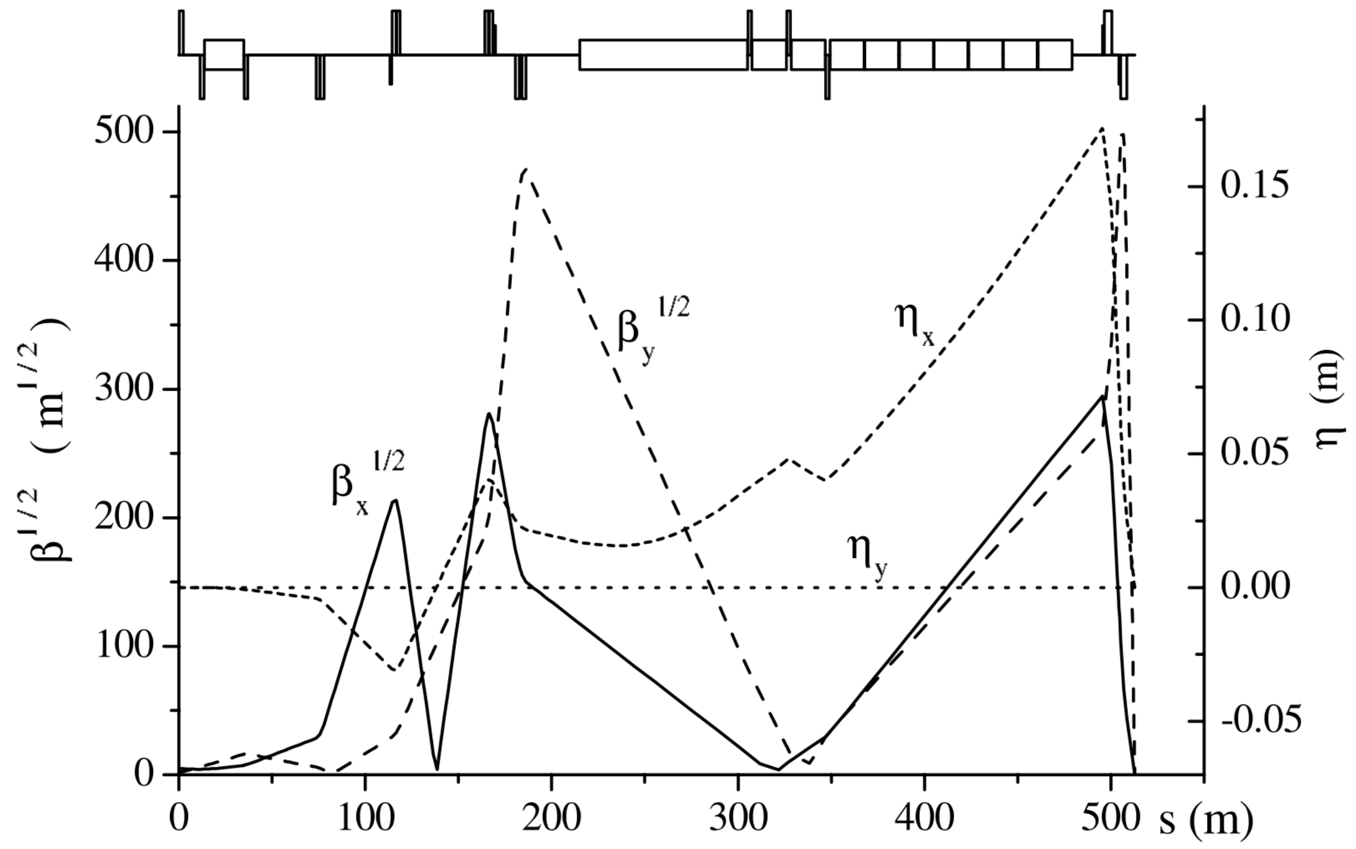
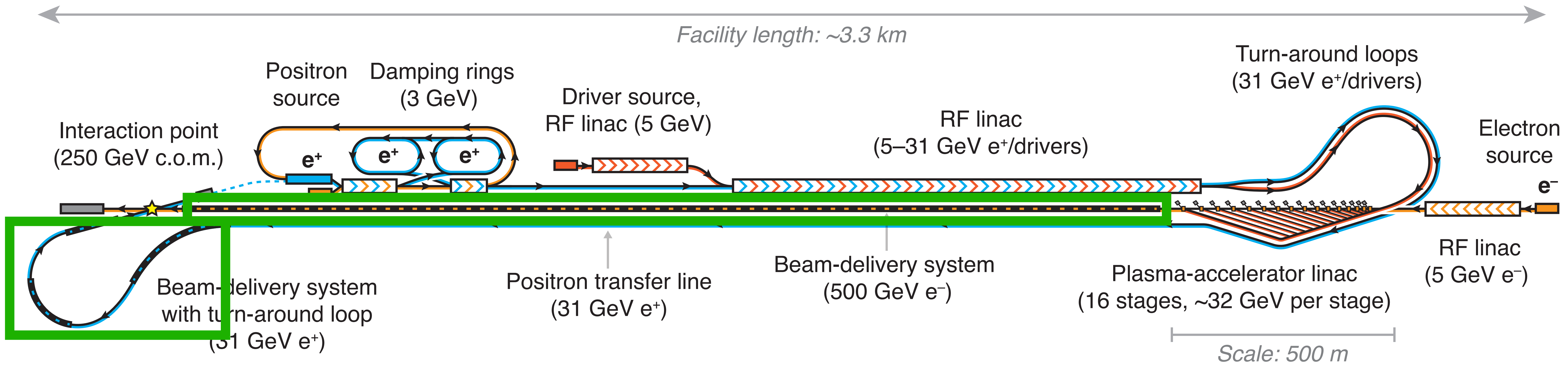
    - Could it be shorter since the emittance is much higher? (*would reduce HALHF footprint considerably*)



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



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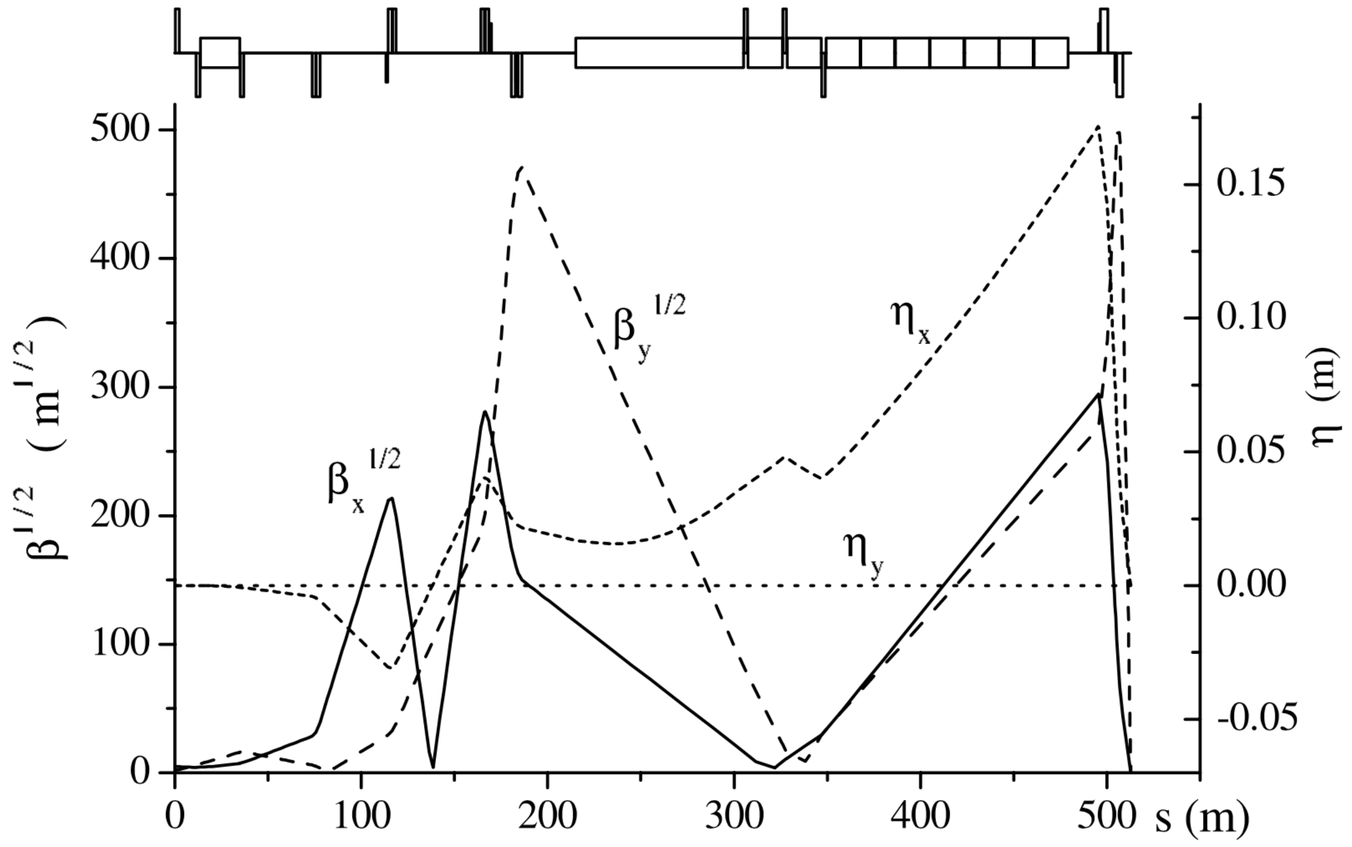

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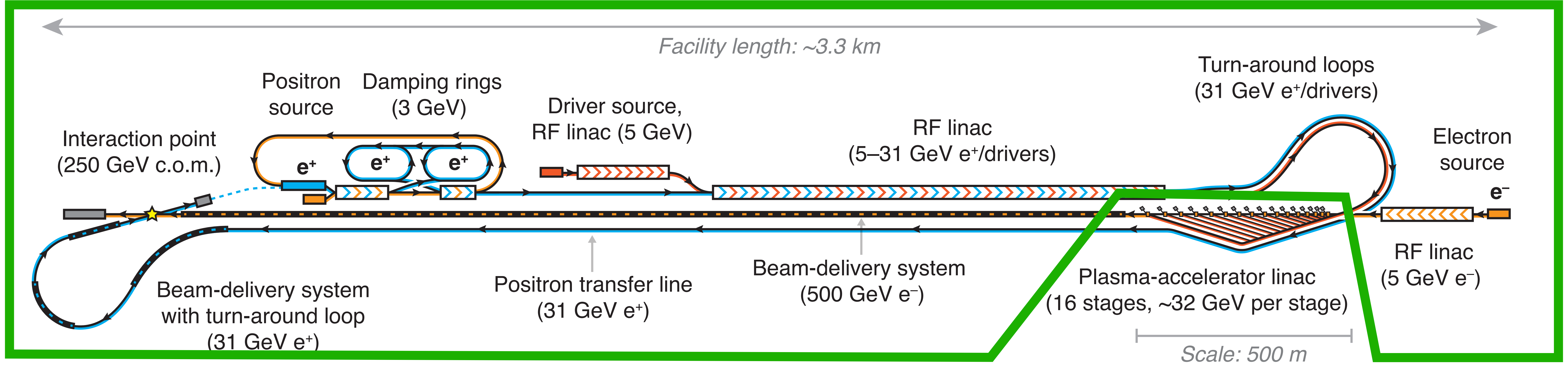
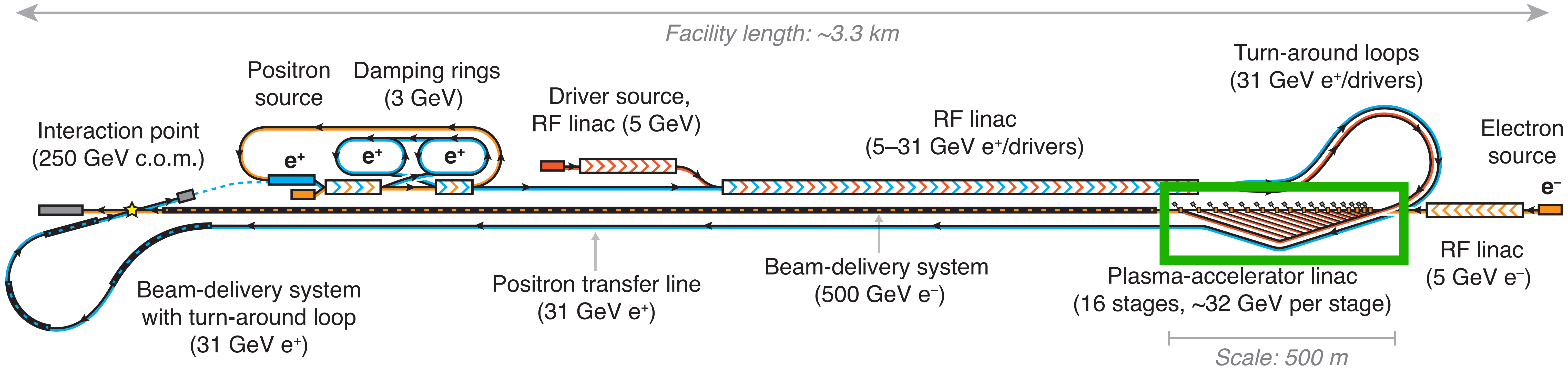
- **Conventional accelerator expertise required!**



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

- Towards high energy:
  - Staging with full beam transmission
  - Multi-stage driver distribution



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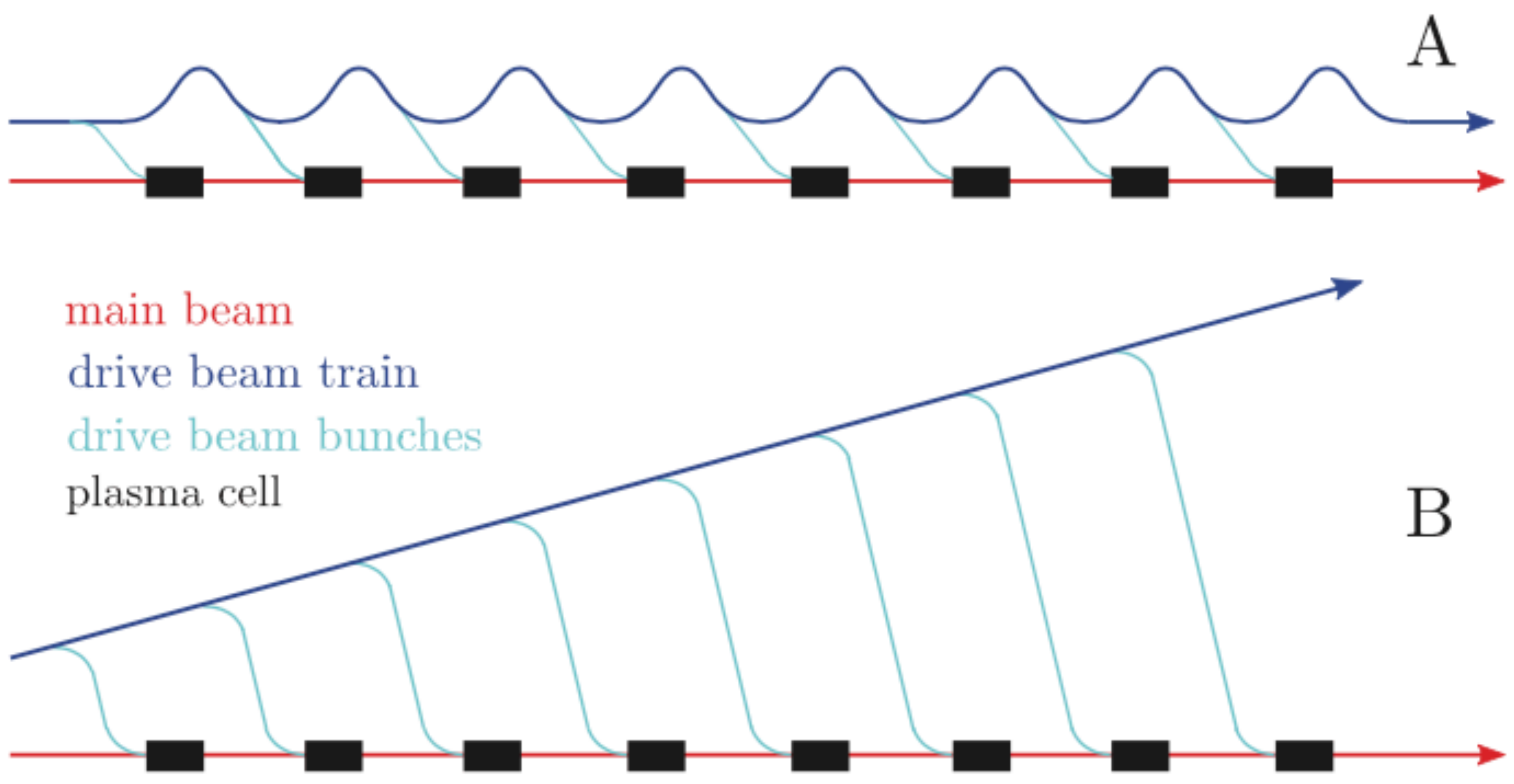
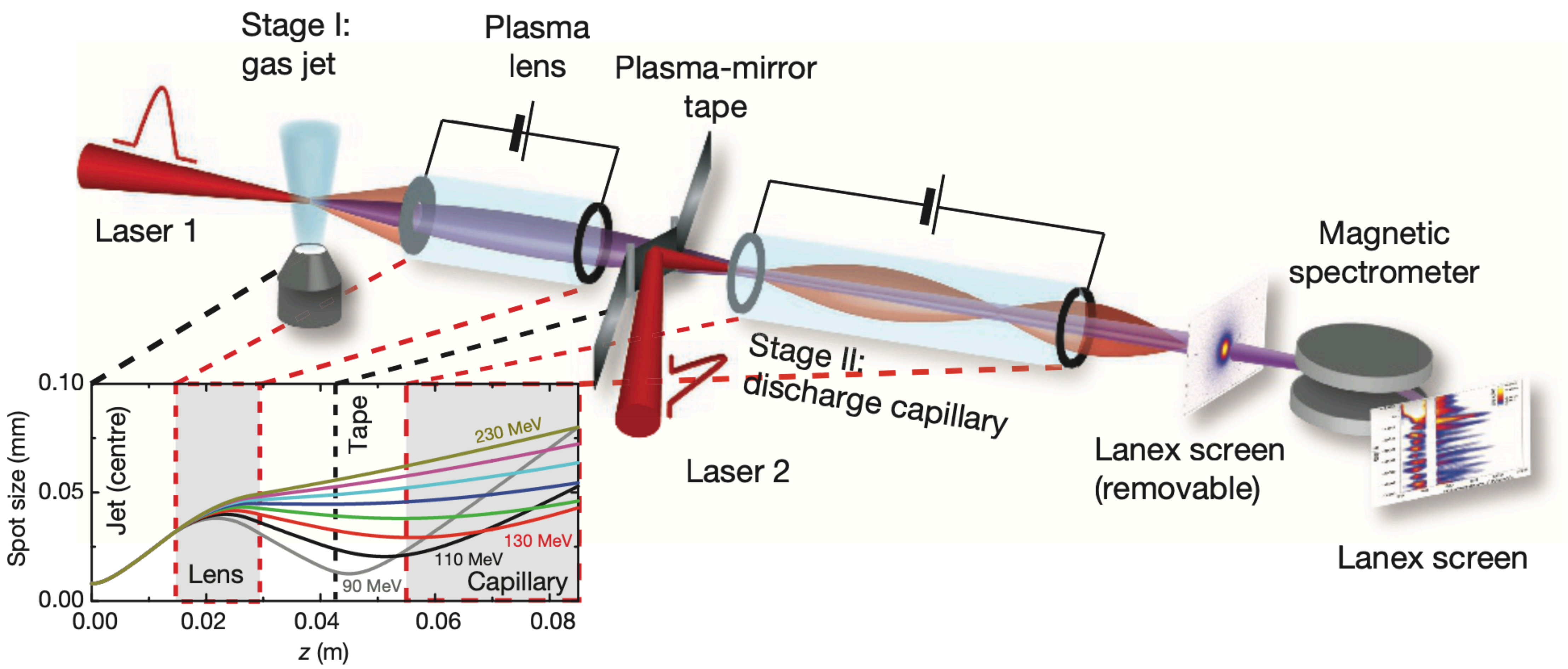


From: Pfingstner et al. (Proc. IPAC 2016)



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

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

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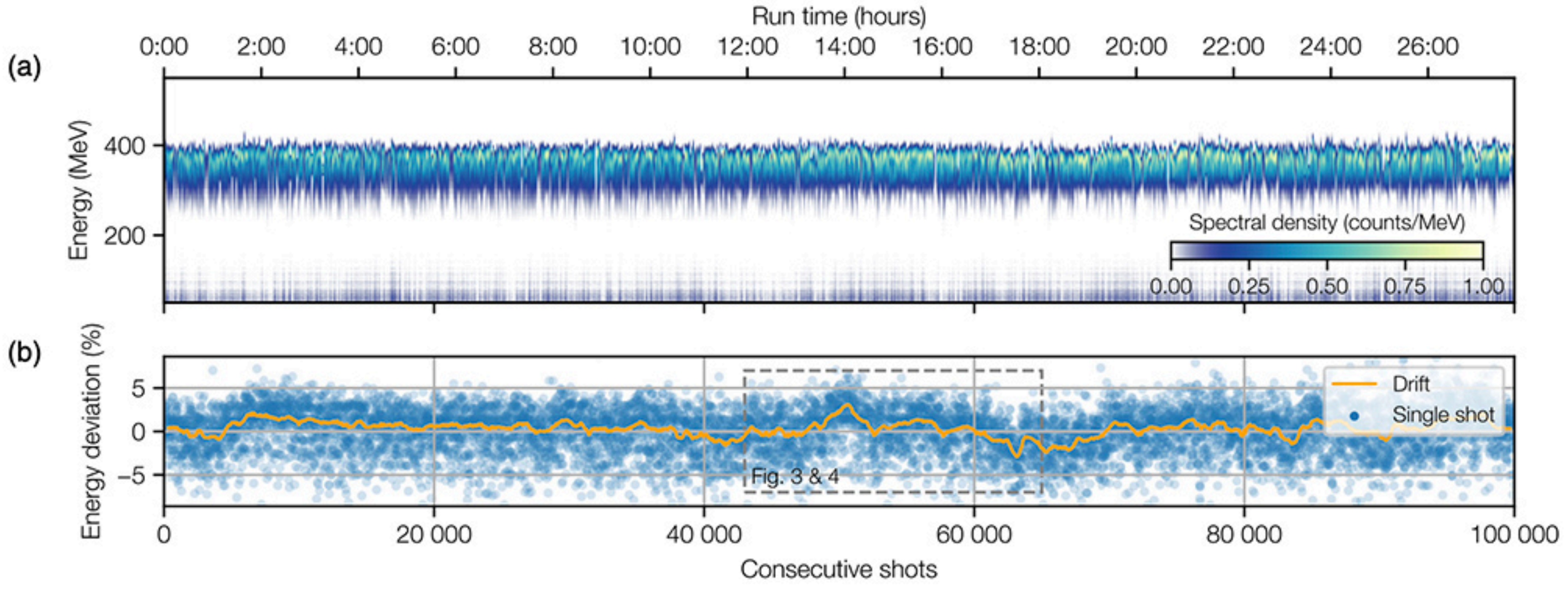
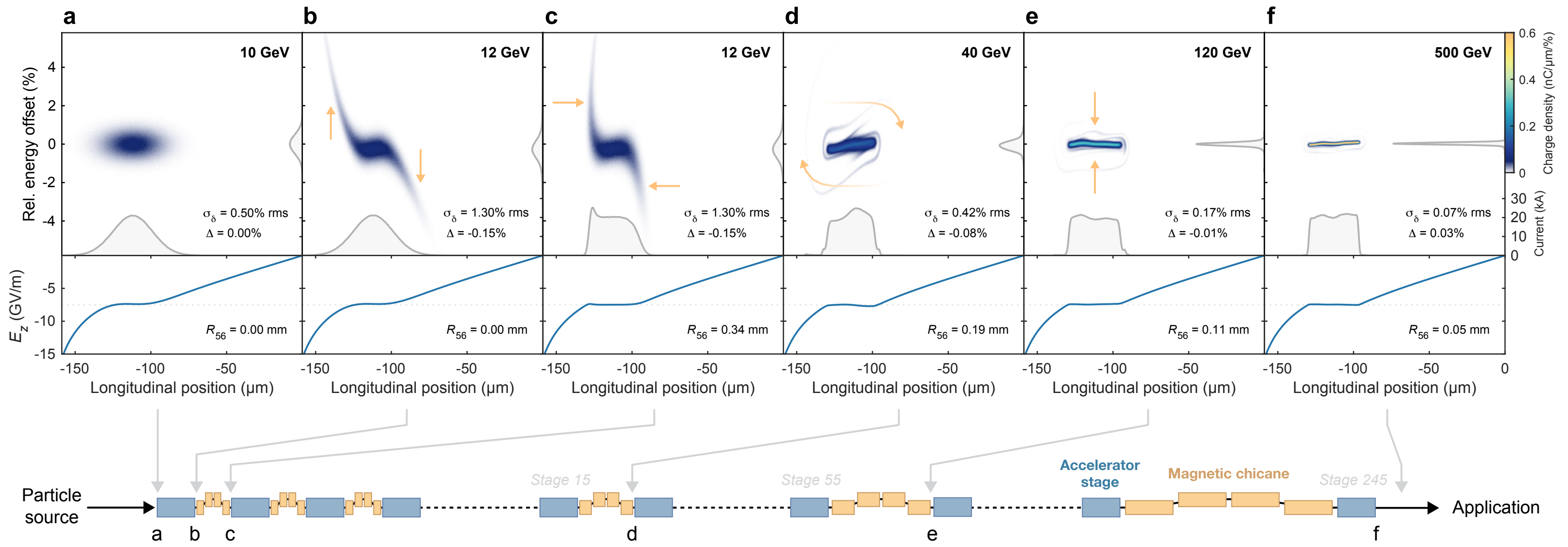
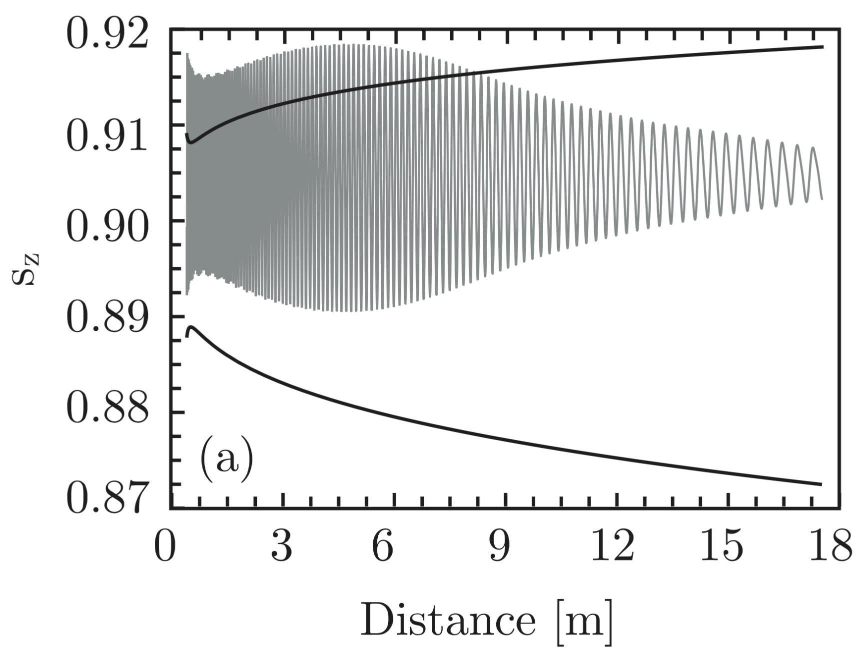
  - Multi-stage driver distribution
- Towards high beam quality:
  - Transverse and longitudinal stability
  - Emittance and energy-spread preservation
  - Spin-polarisation preservation



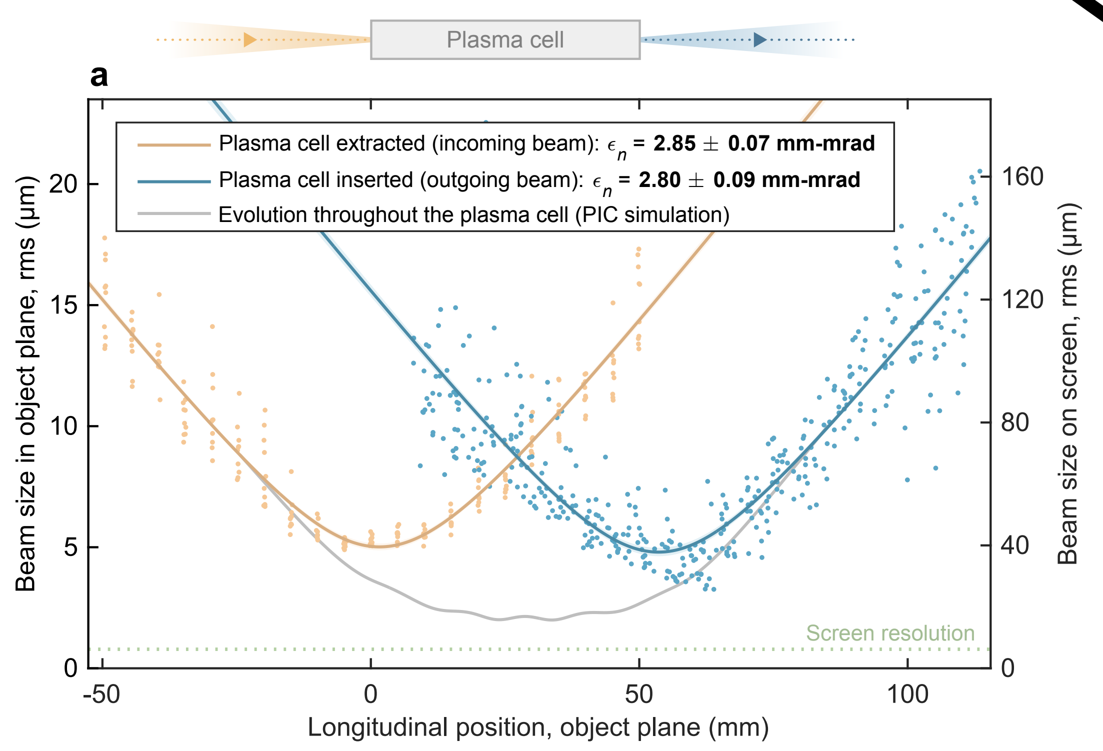
From: Maier et al., Phys. Rev. X 10, 031039 (2020).



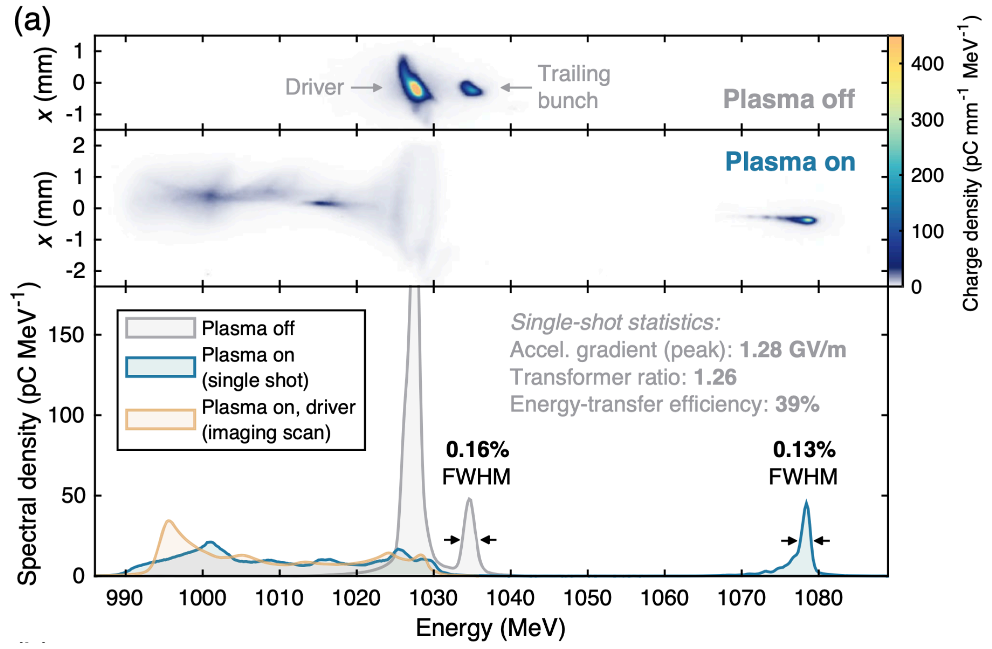
From: Lindstrøm (arXiv: 2104.14460).



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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- Towards high beam quality:
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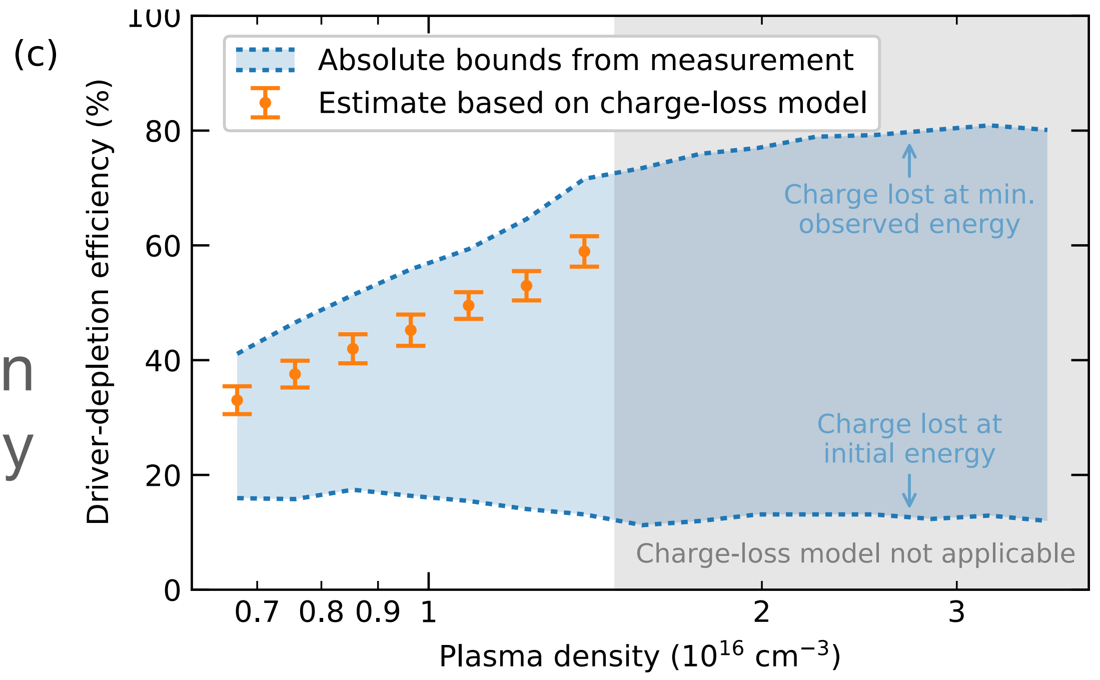
  - Spin-polarisation preservation
- Towards high beam power:
  - High-overall efficiency (wall-plug to beam)
  - Repetition rate
  - Plasma-cell cooling ➞ ***research at Oxford***

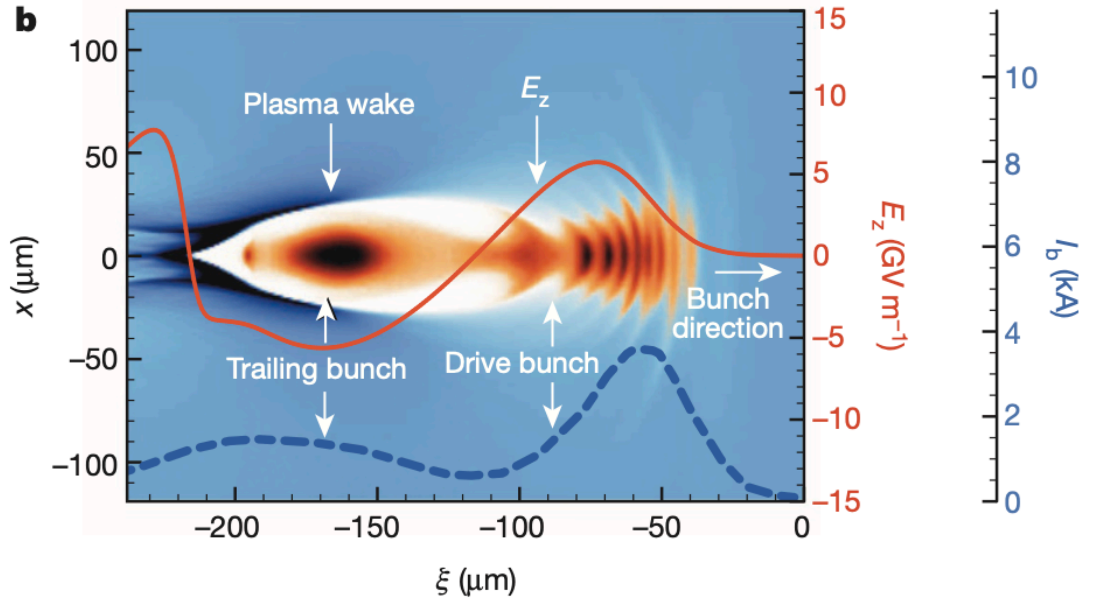
Depletion efficiency

(Must be achieved simultaneously)

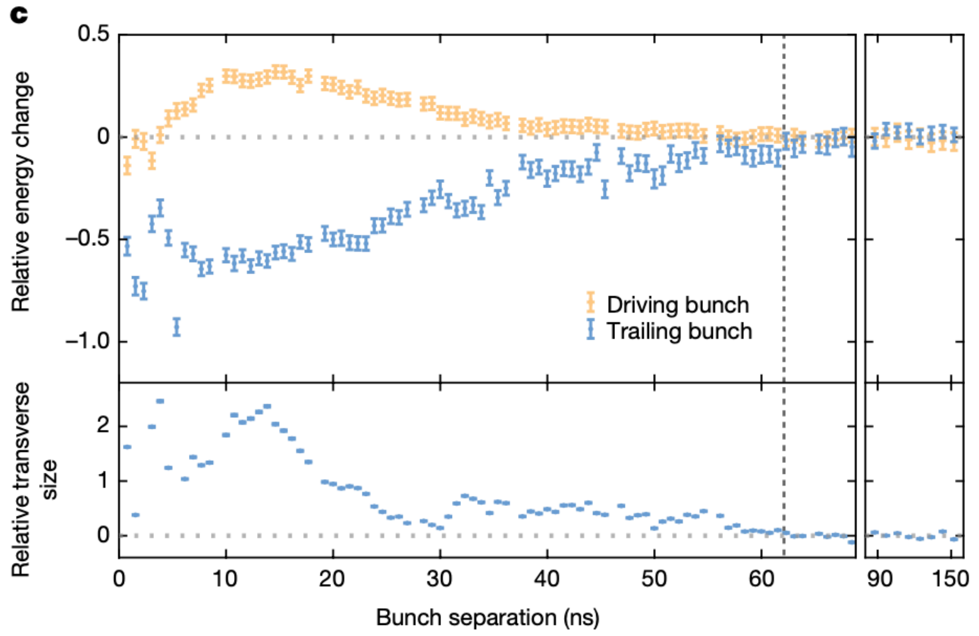
Extraction efficiency



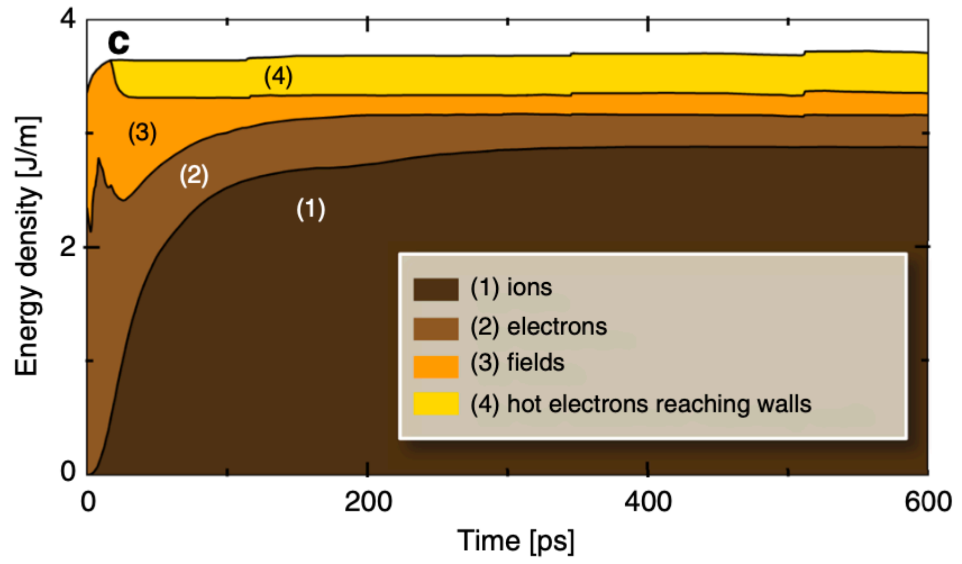
From: Peña et al. (arXiv:2305.09581)



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



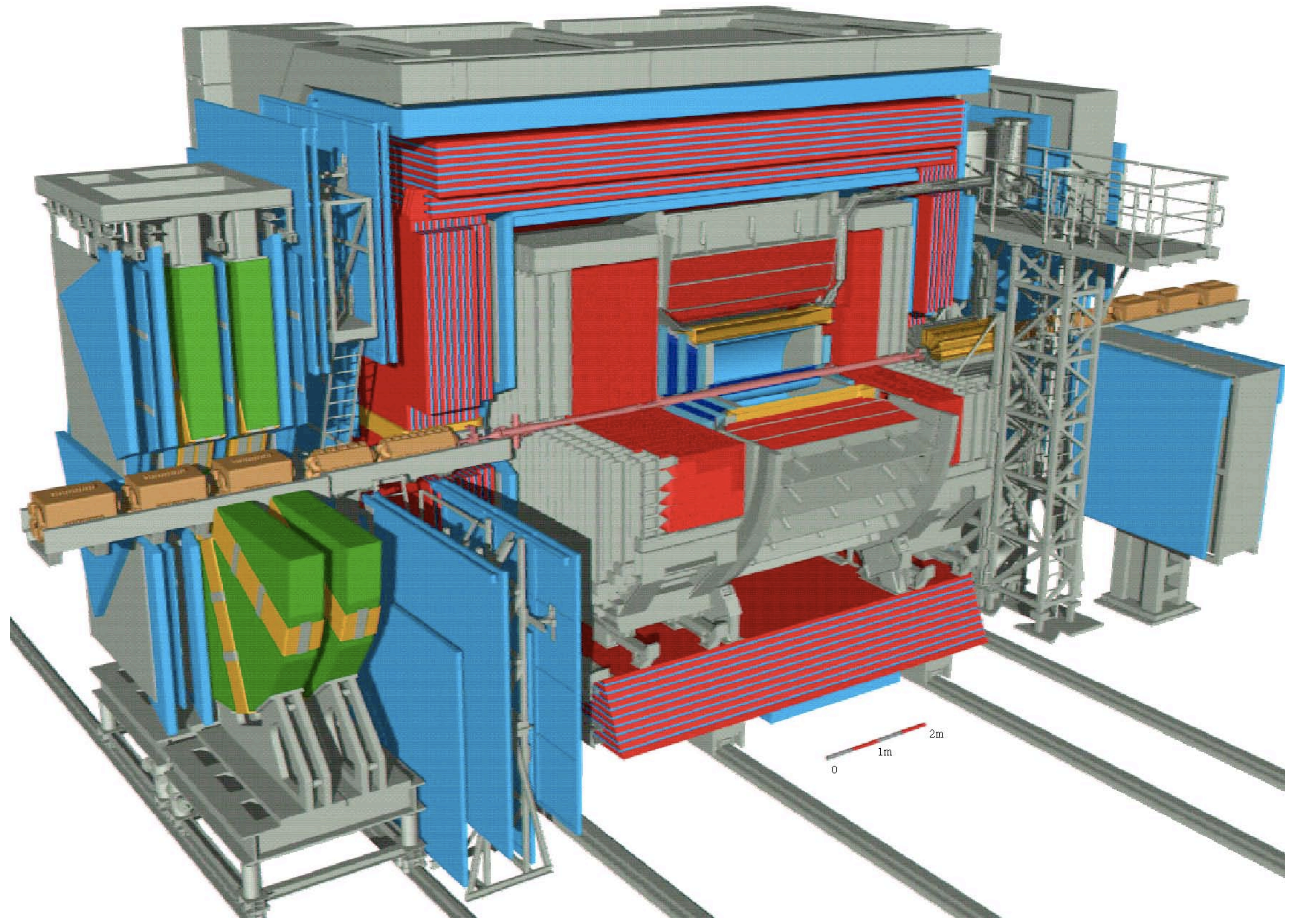
From: D'Arcy et al., Nature 603, 58 (2022).



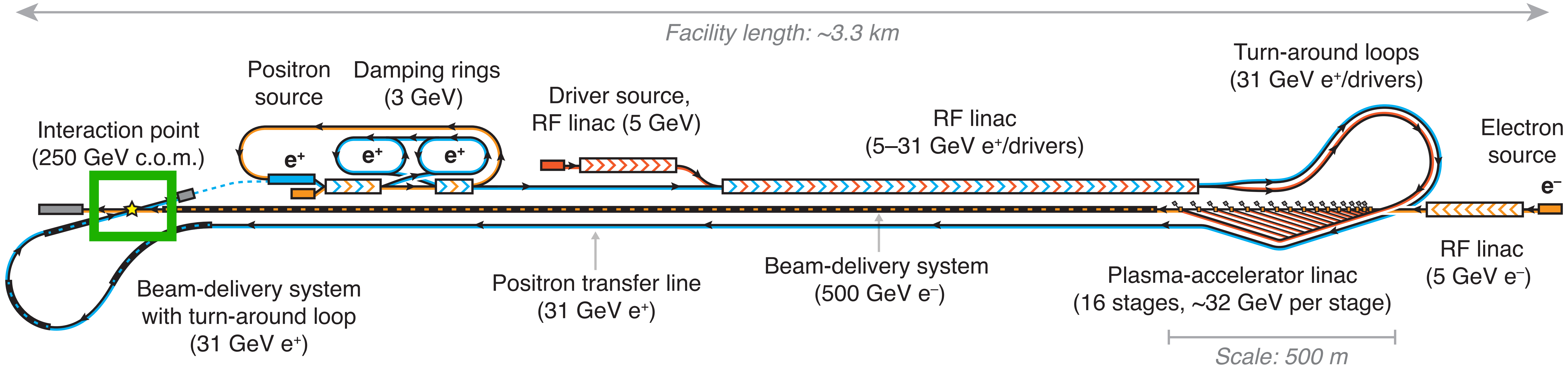
From: Zgadzaj et al.,
Nat. Commun. 11, 4753 (2020)

Innovations required: **Physics / Detector Studies**

- >Asymmetric beam energies ➞ boosted topologies (γ ~ 2)
- >Lower than HERA boost (γ ~3)… but different physics



ZEUS detector at HERA



Innovations required: **Physics / Detector Studies**

- Asymmetric beam energies ➞ boosted topologies (γ ~ 2)
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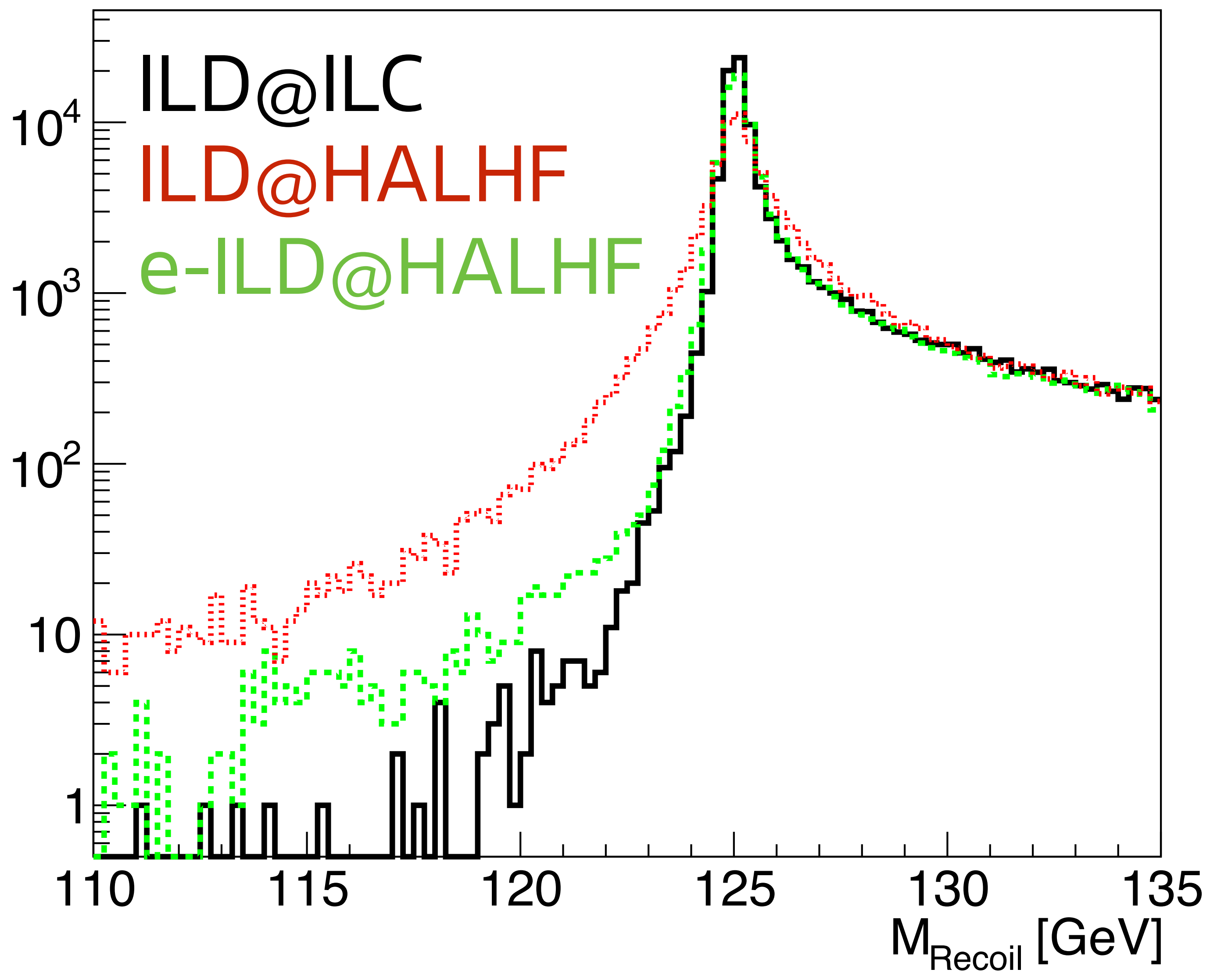
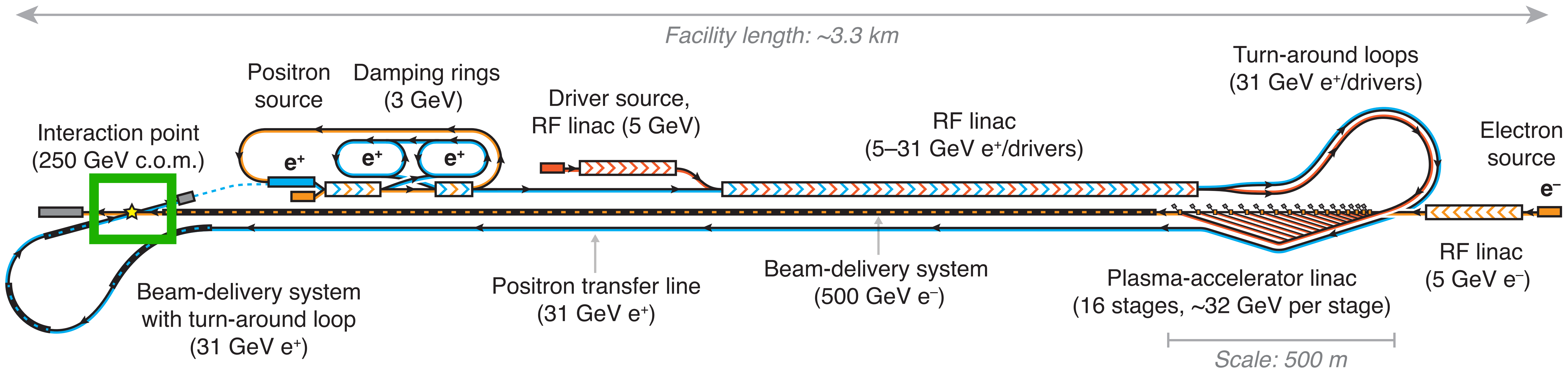
- Preliminary investigation of the HALHF parameters for the ILD with a long barrel shows promise
- A ‘real’ detector design required



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



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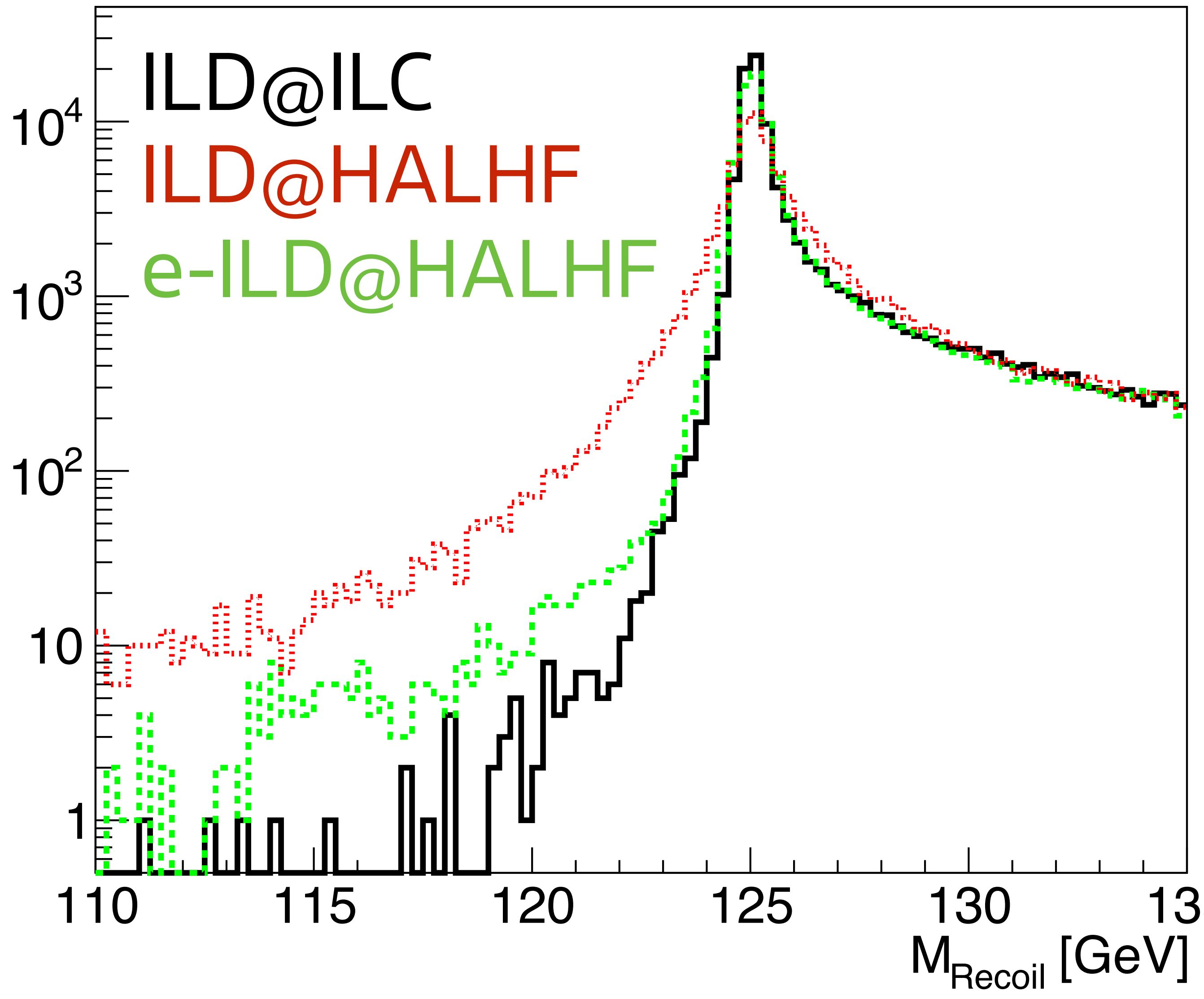

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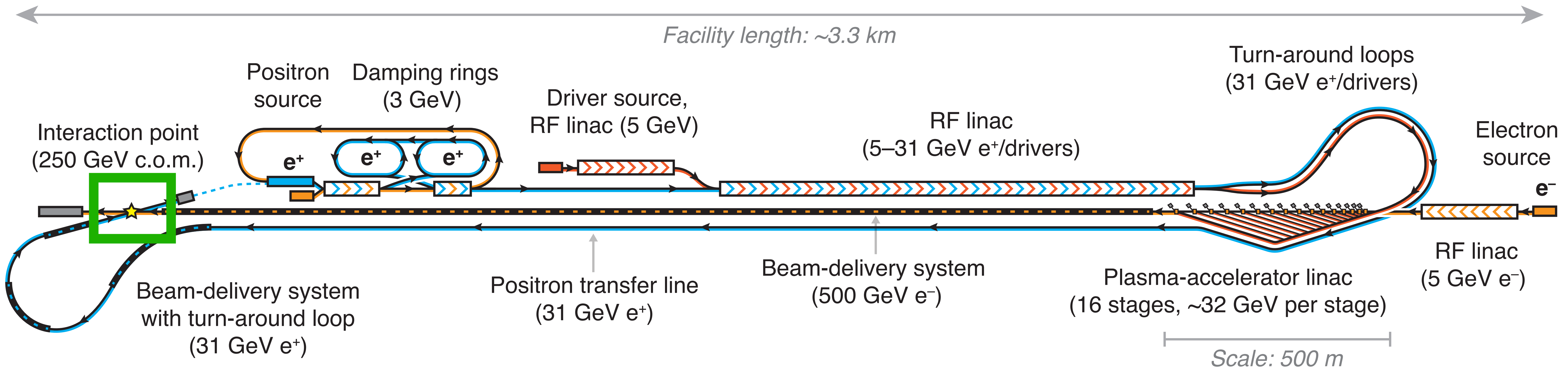
- **Particle physics expertise required!**



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Rough timeline for HALHF (and beyond)

> *Short term (0–5 yrs):* Pre-CDR* & CDR

European Strategy Update

***Feasibility study to be submitted as input to the next ESPP Strategy Update**

(deadline 31st March 2025)

Timeline (approximate / aggressive / aspirational)				
0–5 years	**5–10 years**	**10–15 years**	**15–20 years**	**20+ years**
Pre-CDR & CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals) First proof-of-principle experimentation				

🟨 *Feasibility study*
⬜ *R&D (exp. & theory)*
🟩 *HEP facility (earliest start of construction)*

Rough timeline for HALHF (and beyond)

- *Short term (0–5 yrs):* Pre-CDR* & CDR
- *Near term (0–10 yrs):* Much Plasma R&D required!

Timeline (approximate / aggressive / aspirational)				
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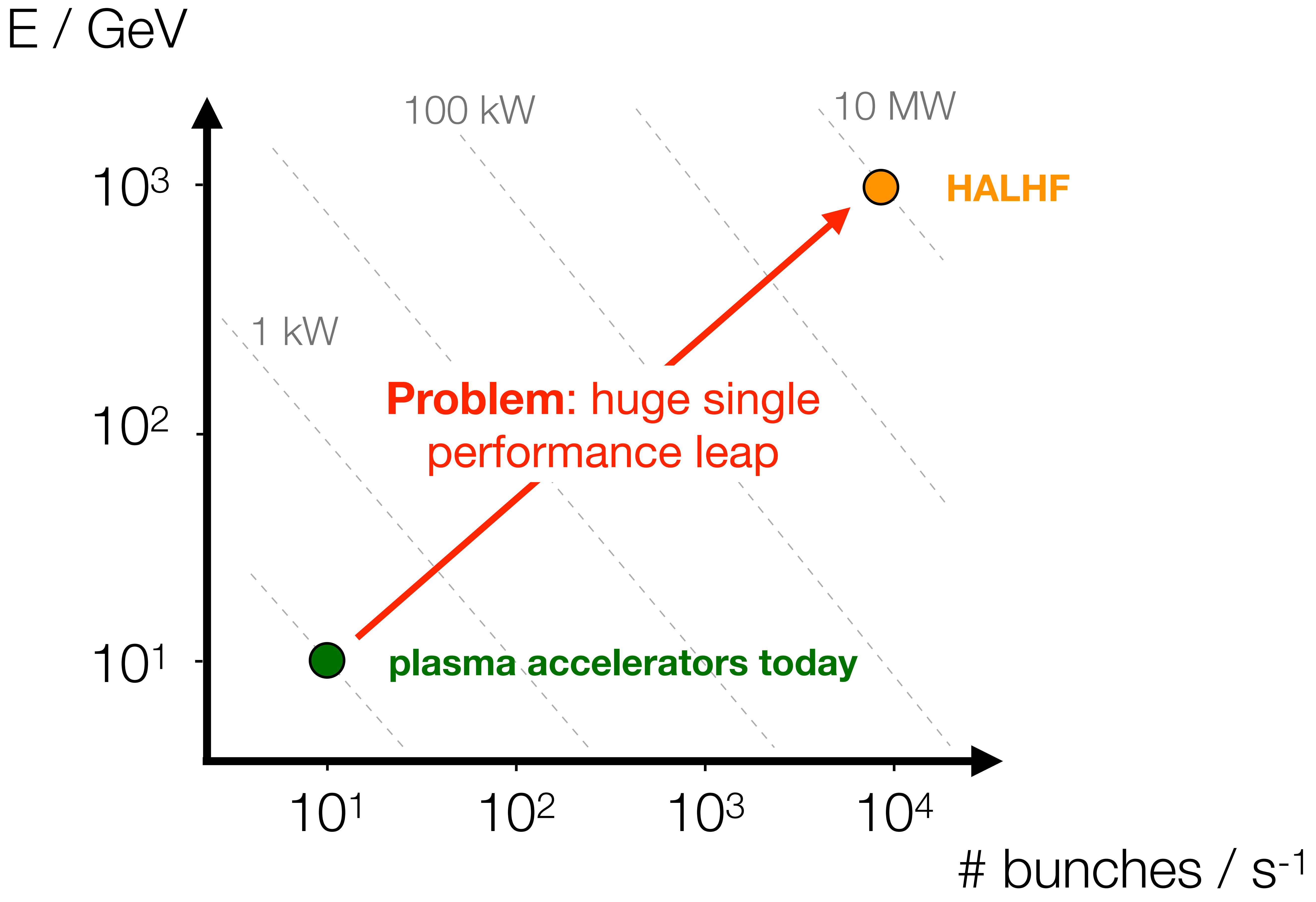
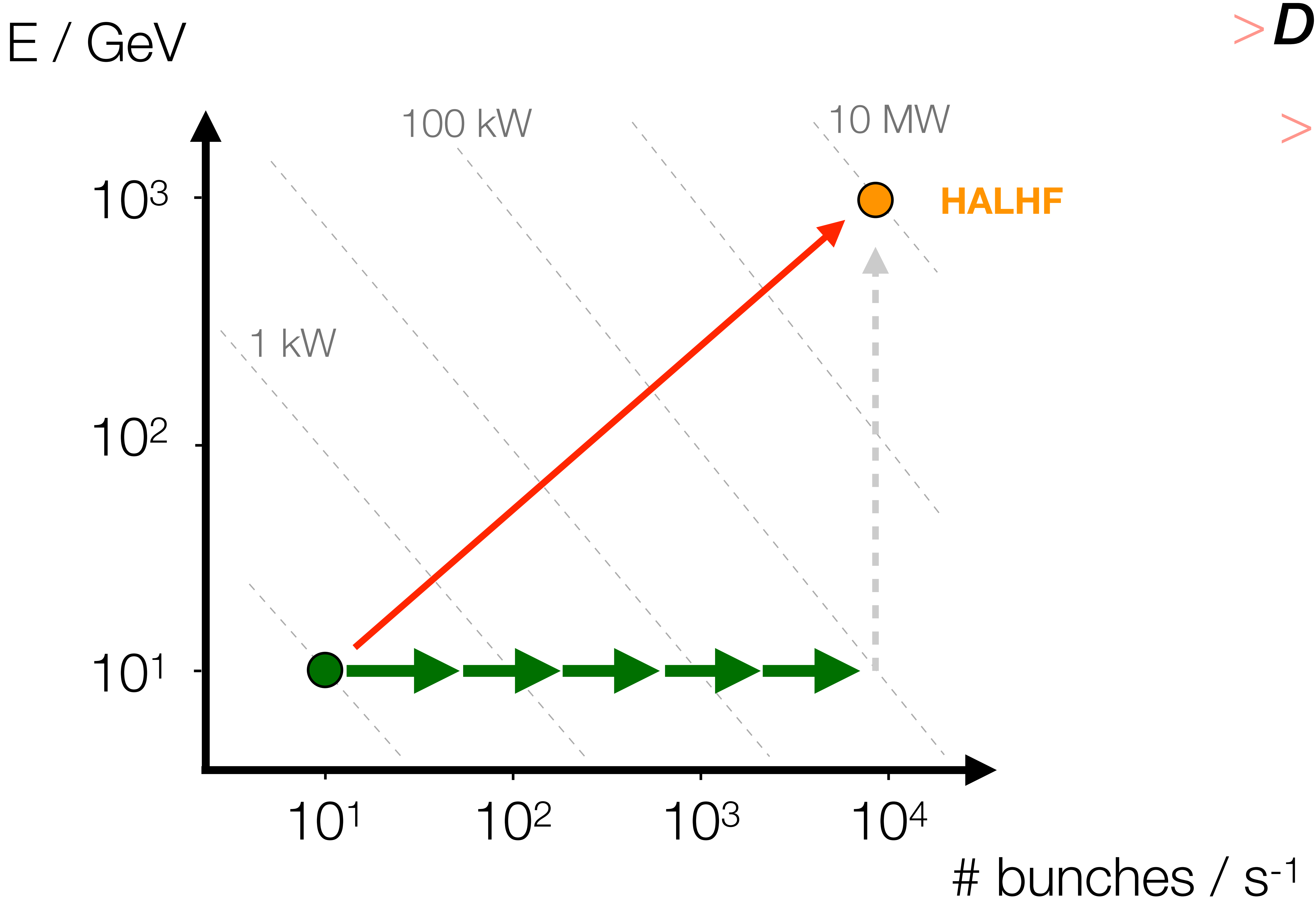
Stepping stone facilities: **Plasma tech Demonstrators for HALHF**



Problem: huge single performance leap

Stepping stone facilities: **Plasma tech Demonstrators for HALHF**



- ***Decouple the challenge***:
  - Free-electron lasers (FELs) need ‘low’ energy (*single stage*) at high repetition rate

X-ray FEL

Image source: G. Stewart/SLAC.

Stepping stone facilities: **Plasma tech Demonstrators for HALHF**

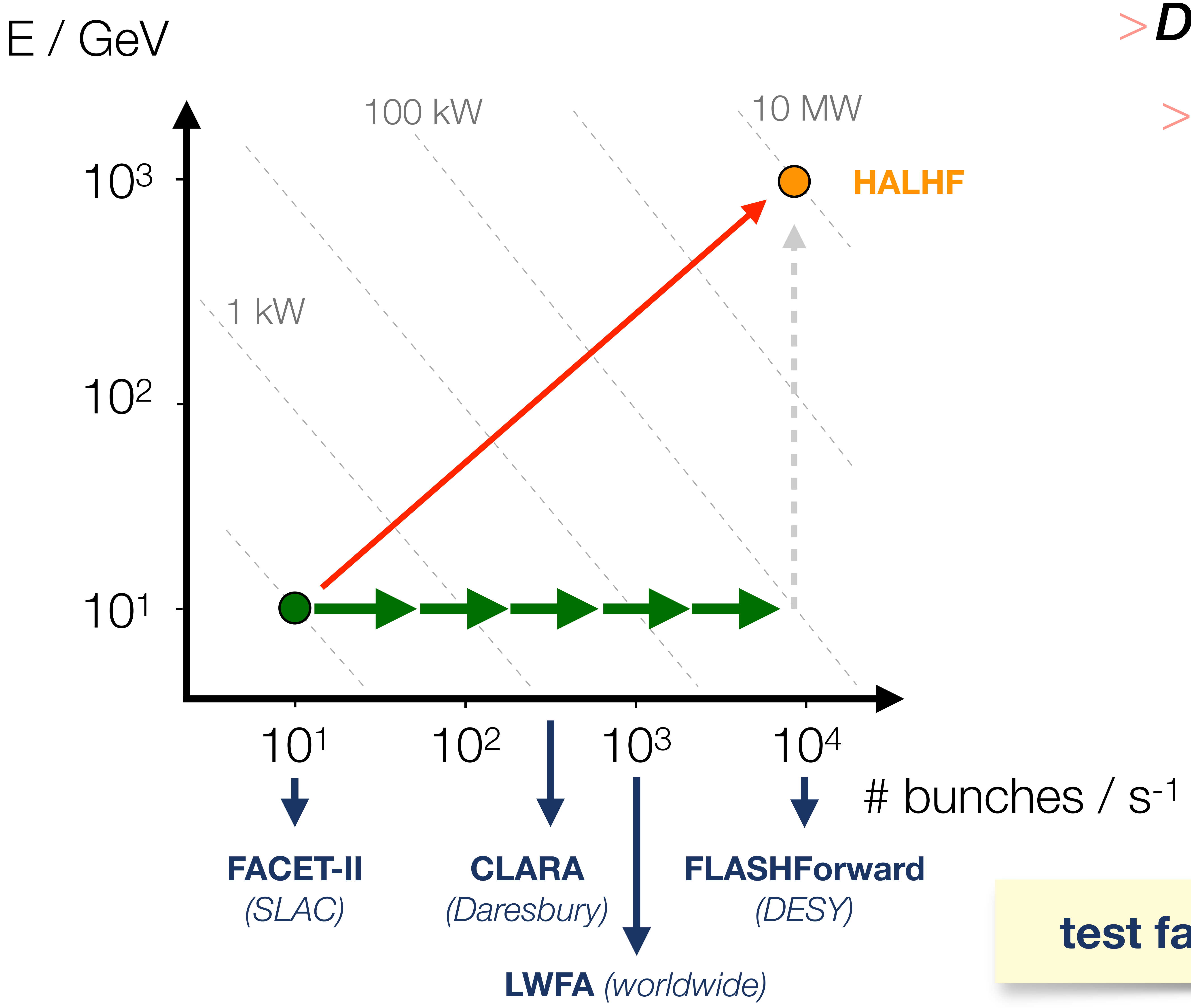


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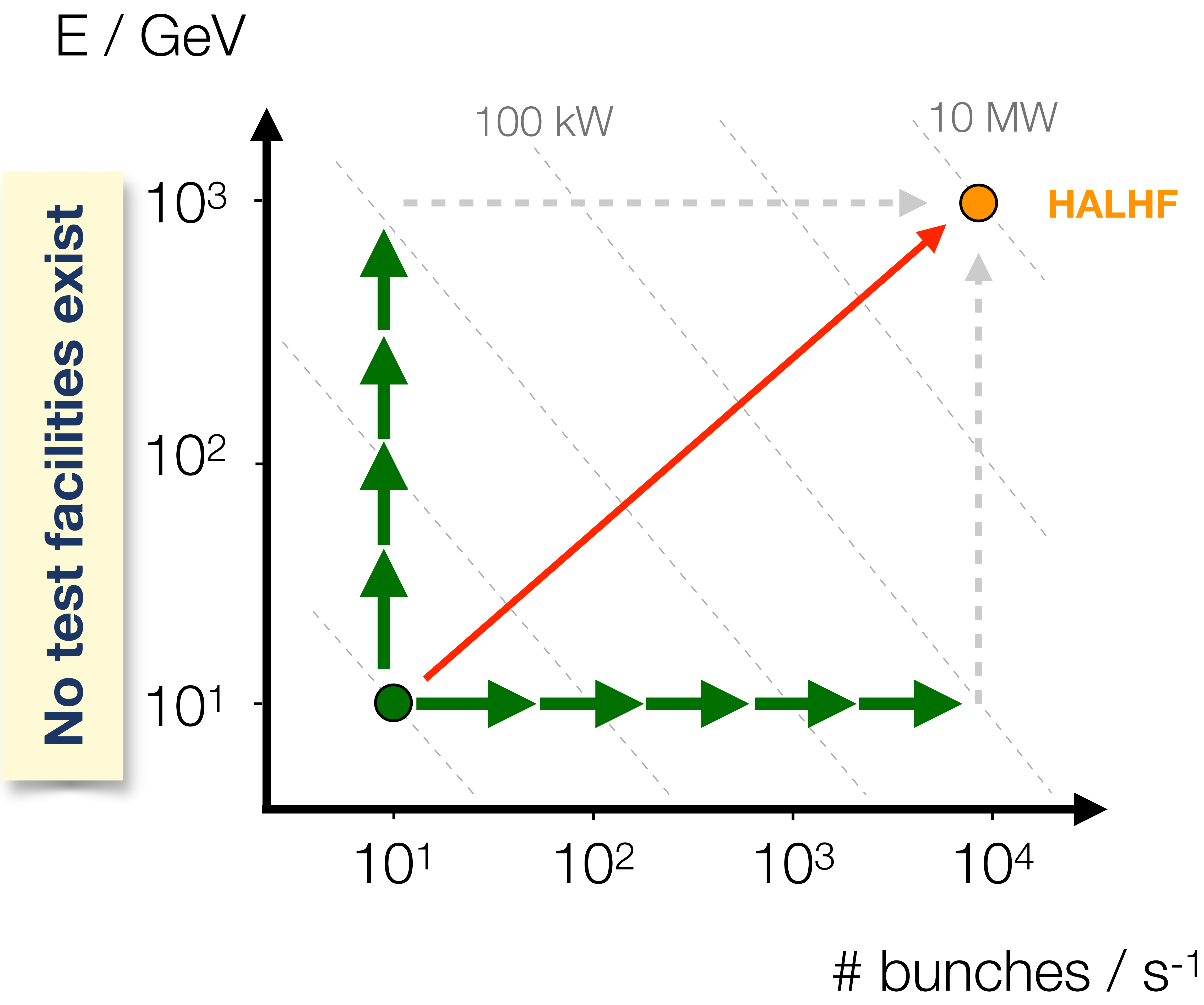
Image source: G. Stewart/SLAC.

test facilities exist

Stepping stone facilities: **Plasma tech Demonstrators for HALHF**



- ***Decouple the challenge***:
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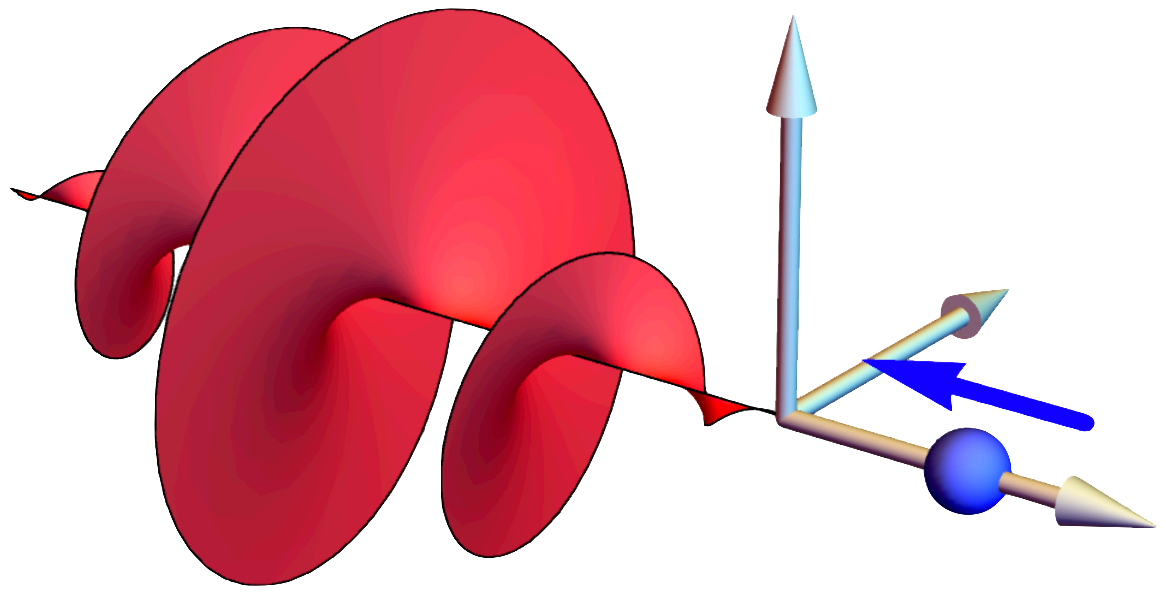
  - Strong-field QED needs 'high' energy (*multiple stages*) at low repetition rate

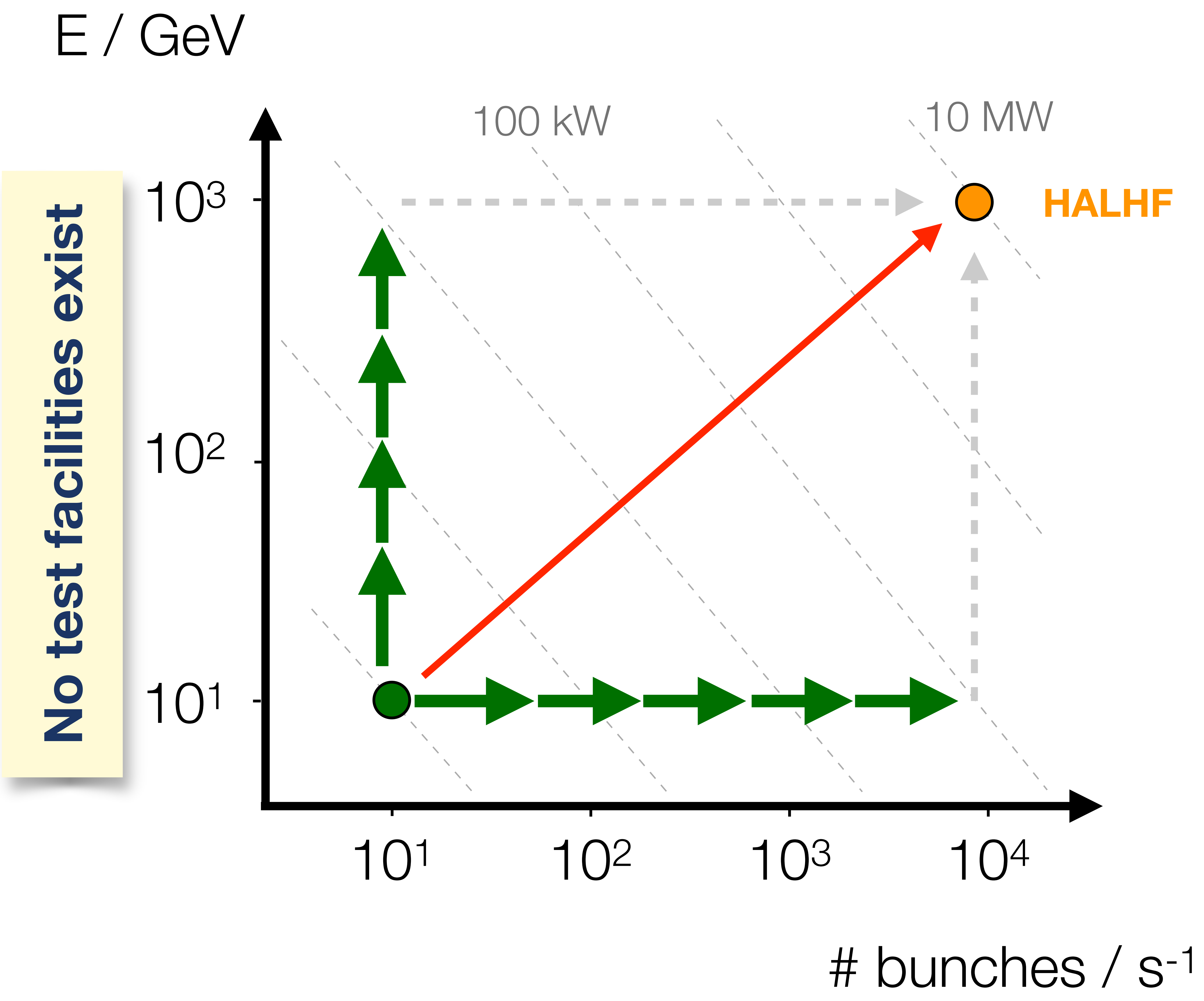
Strong-field QED



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

- ***A dedicated staging facility is required to realise the necessary progress***

Stepping stone facilities: **Plasma tech Demonstrators for HALHF**



- ***Decouple the challenge***:
  - Free-electron lasers (FELs) need 'low' energy (*single stage*) at high repetition rate
  - Strong-field QED needs 'high' energy (*multiple stages*) at low repetition rate
- ***Intermediate infrastructure for HEP use:***
  - Test-beam facility for detector development
  - Fixed-target exp for dark-matter search
  - Plasma-based electron linac for LHeC

- ***A dedicated staging facility is required to realise the necessary progress***

Rough timeline for HALHF (and beyond)

- *Short term (0–5 yrs):* Pre-CDR & CDR
- *Near term (5–15 yrs):* Tech. Demonstrators — **strong-field QED, X-ray FEL, and beyond**

Timeline (approximate / aggressive / aspirational)				
0–5 years	**5–10 years**	**10–15 years**	**15–20 years**	**20+ years**
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	Demonstration of: Preserved beam quality, high rep. rate, plasma temporal uniformity & cell cooling	**Avg. power tech demonstrator** X-ray FEL (20 GeV e^-)		

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- *Long term (15–20 yrs):* Delivery of HALHF — **intense R&D required**

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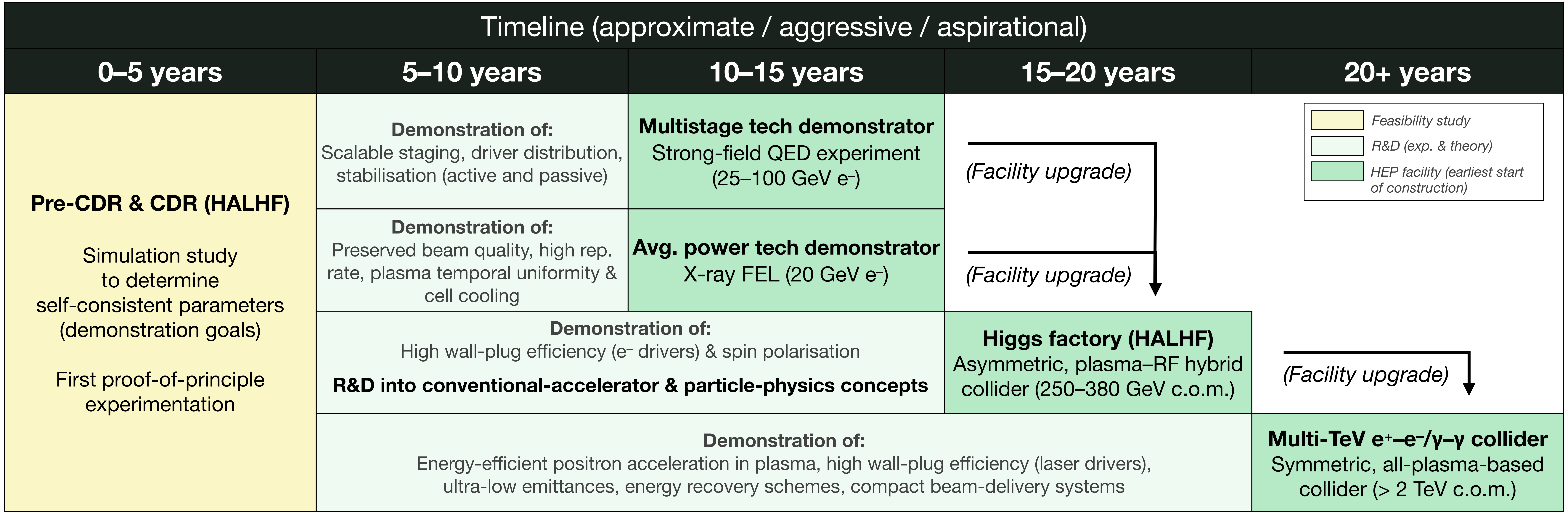
	Demonstration of: Preserved beam quality, high rep. rate, plasma temporal uniformity & cell cooling	**Avg. power tech demonstrator** X-ray FEL (20 GeV e^-)	*(Facility upgrade)*	
	Demonstration of: High wall-plug efficiency (e^- drivers) & spin polarisation **R&D into conventional-accelerator & particle-physics concepts**		**Higgs factory (HALHF)** Asymmetric, plasma–RF hybrid collider (250–380 GeV c.o.m.)	

Rough timeline for HALHF (and beyond)

- *Short term (0–5 yrs):* Pre-CDR & CDR
- *Near term (5–15 yrs):* Tech. Demonstrators — **strong-field QED, X-ray FEL, and beyond**
- *Long term (15–20 yrs):* Delivery of HALHF — **intense R&D required**
- *Upgrades (20+ yrs):* Upgrade path for HALHF (many options available)



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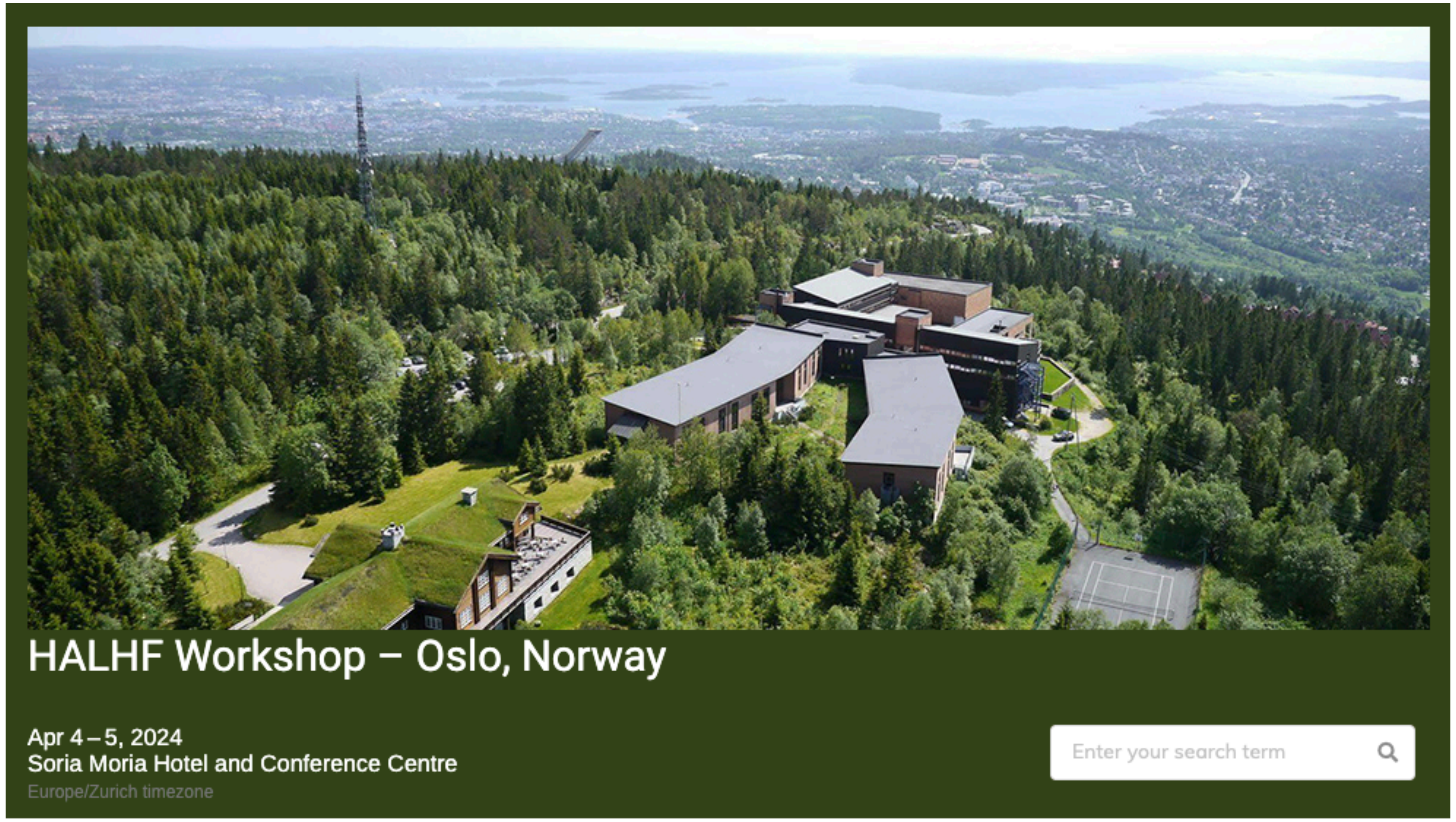
First proof-of-principle experimentation</td><td>Demonstration of:
Scalable staging, driver distribution, stabilisation (active and passive)</td><td>Multistage tech demonstrator
Strong-field QED experiment (25–100 GeV e^-)</td><td><i>(Facility upgrade)</i></td><td rowspan="2">🟨 <i>Feasibility study</i>
⬜ <i>R&D (exp. & theory)</i>
🟩 <i>HEP facility (earliest start of construction)</i></td></tr>
<tr><td>Demonstration of:
Preserved beam quality, high rep. rate, plasma temporal uniformity & cell cooling</td><td>Avg. power tech demonstrator
X-ray FEL (20 GeV e^-)</td><td><i>(Facility upgrade)</i></td></tr>
<tr><td colspan="2">Demonstration of:
High wall-plug efficiency (e^- drivers) & spin polarisation
R&D into conventional-accelerator & particle-physics concepts</td><td>Higgs factory (HALHF)
Asymmetric, plasma–RF hybrid collider (250–380 GeV c.o.m.)</td><td><i>(Facility upgrade)</i></td></tr>
<tr><td colspan="3">Demonstration of:
Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser drivers), ultra-low emittances, energy recovery schemes, compact beam-delivery systems</td><td>Multi-TeV e^+–e^-/γ–γ collider
Symmetric, all-plasma-based collider (> 2 TeV c.o.m.)</td></tr>
</table>

HALHF Collaboration

- **HALHF Kick-off meeting (DESY)**
  - 23/10/23
- **HALHF Monthly meetings (online)**
  - 18/12/23, 29/01/24, 26/02/24
- **HALHF Workshop (Oslo, Norway)** →
  - 04-05/04/24
- **HALHF ‘Experts’ meeting (Erice, Sicily)**
  - 03-08/10/24

- **Interested? Get in touch!**



HALHF Workshop – Oslo, Norway

Apr 4 – 5, 2024
Soria Moria Hotel and Conference Centre
Europe/Zurich timezone

Conclusions — HALHF

- **The HALHF concept proposes a compact, cheaper, greener, possibly quicker Higgs factory**
- **HALHF benefits from maximal asymmetry:** energy — charge — emittance
- **High risk/high reward:** less mature than RF technology but cost is only 'national-scale' (few $B)
- **Upgrade path to higher energy and output possible:** not just a one-trick pony
- **Much targeted (plasma and RF) R&D still required:** a decade of significant work
- **Challenges outlined by the community identify issues requiring more R&D:** help to guide design decisions towards '*HALHF 2.0*'

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