Novel-Accelerator-Based Colliders

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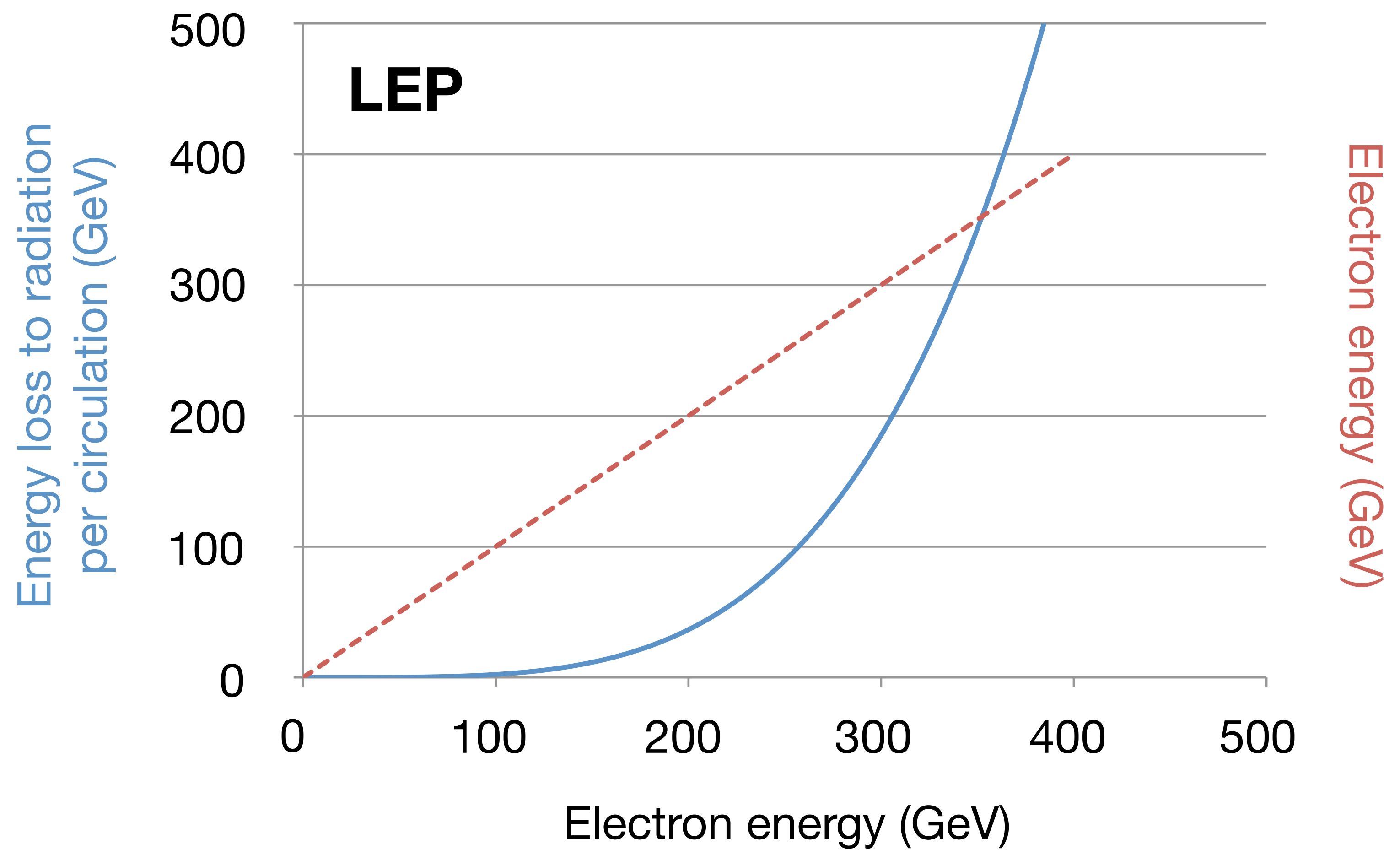
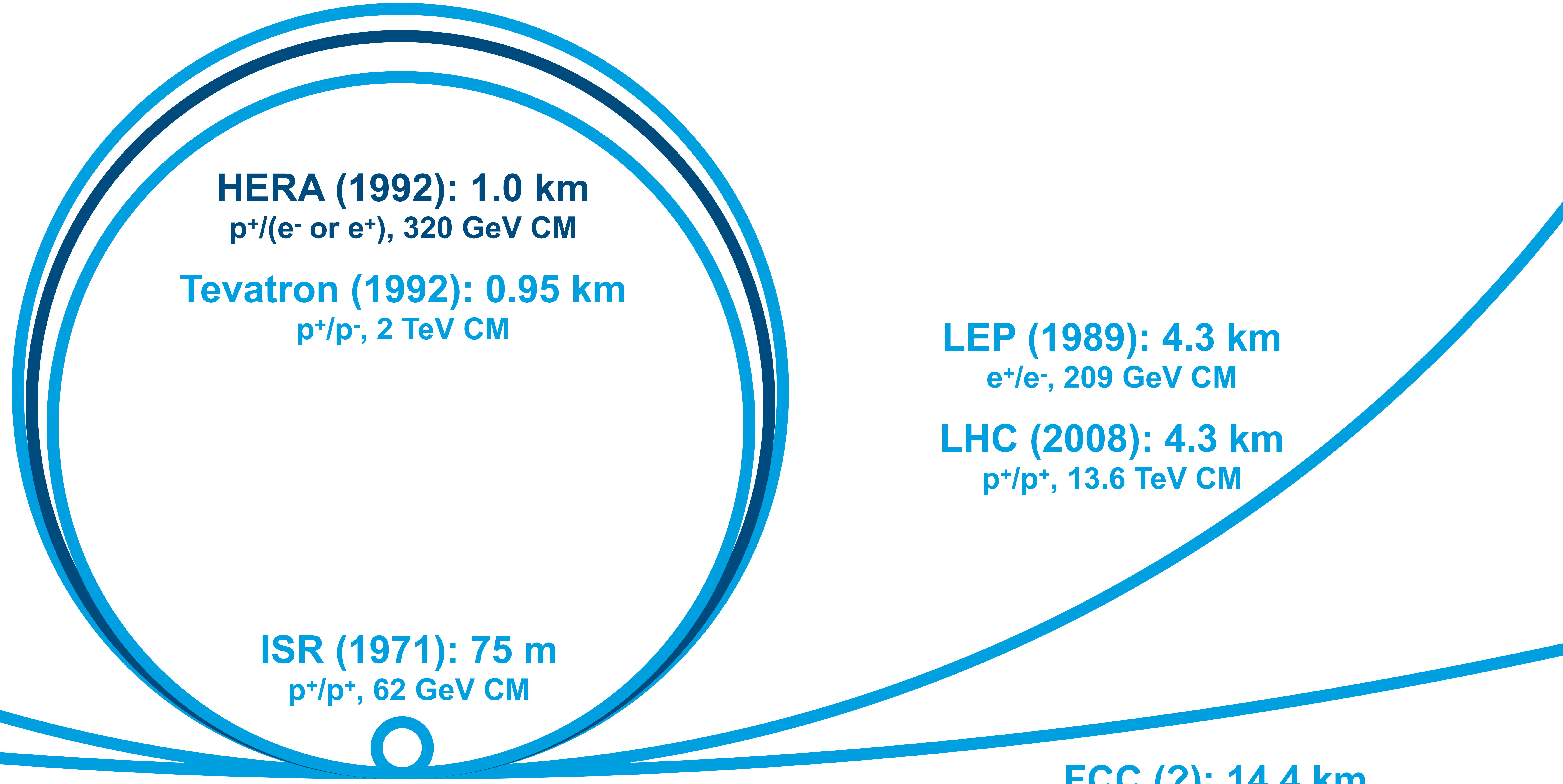
25th Sept 2024 | ECFA-UK Meeting | IPPP, University of Durham

Particle colliders have been growing in size

Magnet technology and synchrotron radiation cause unfavourable scaling to higher energies



$$\Delta W_{syn} \propto \frac{1}{r^2} \frac{W_{kin}^4}{(m_e c^2)^4}$$



SppS (1981): 1.1 km radius
p^+/p^-, 900 GeV CM

HERA (1992): 1.0 km
$p^+/(e^-$ or $e^+)$, 320 GeV CM

Tevatron (1992): 0.95 km
p^+/p^-, 2 TeV CM

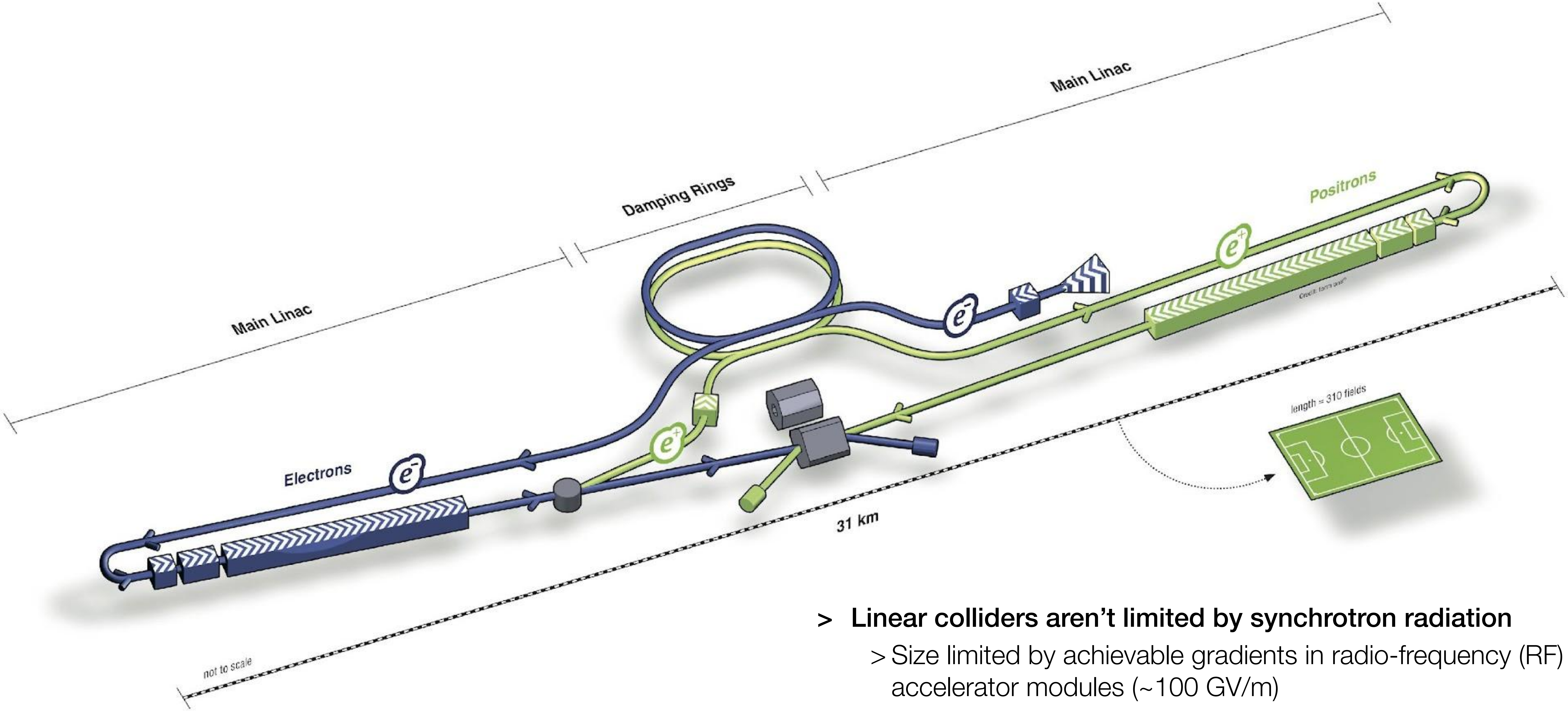
LEP (1989): 4.3 km
e^+/e^-, 209 GeV CM

LHC (2008): 4.3 km
p^+/p^+, 13.6 TeV CM

ISR (1971): 75 m
p^+/p^+, 62 GeV CM

FCC (?): 14.4 km
e^+/e^-, > 365 GeV CM
p+/p+, up to 100 TeV CM

The next step for electron/positron colliders could be linear

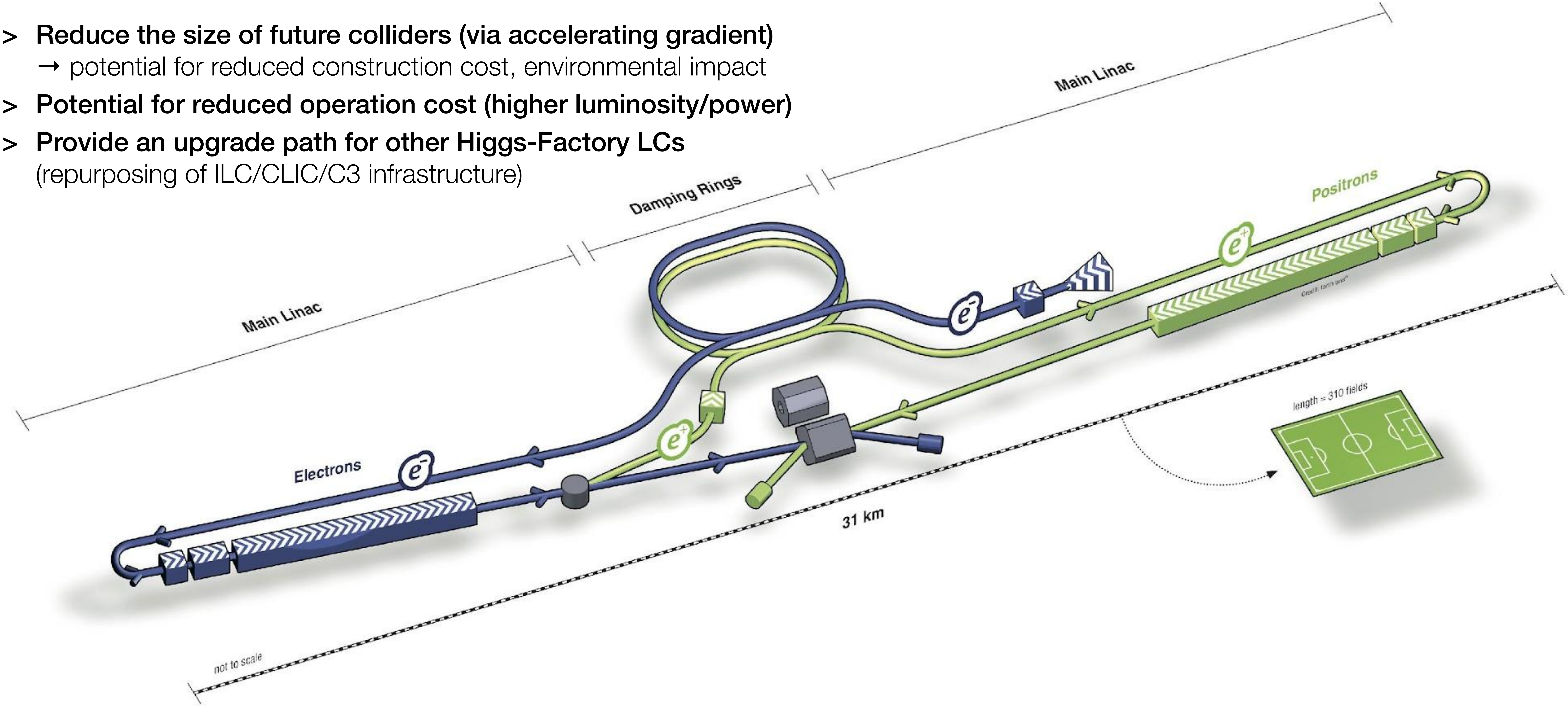


ILC / 500 GeV / 31 km

- **Linear colliders aren't limited by synchrotron radiation**
  - Size limited by achievable gradients in radio-frequency (RF) accelerator modules (~100 GV/m)
  - *Main RF-options*: ILC, CLIC, C^3
- **Still a significant investment $\mathcal{O}(10^{10}$ €) and scale $\mathcal{O}$(10s km)**

The plasma-accelerator (>1 GV/m) mission for particle physics

- **Reduce the size of future colliders (via accelerating gradient)**
  → potential for reduced construction cost, environmental impact
- **Potential for reduced operation cost (higher luminosity/power)**
- **Provide an upgrade path for other Higgs-Factory LCs**
  (repurposing of ILC/CLIC/C3 infrastructure)



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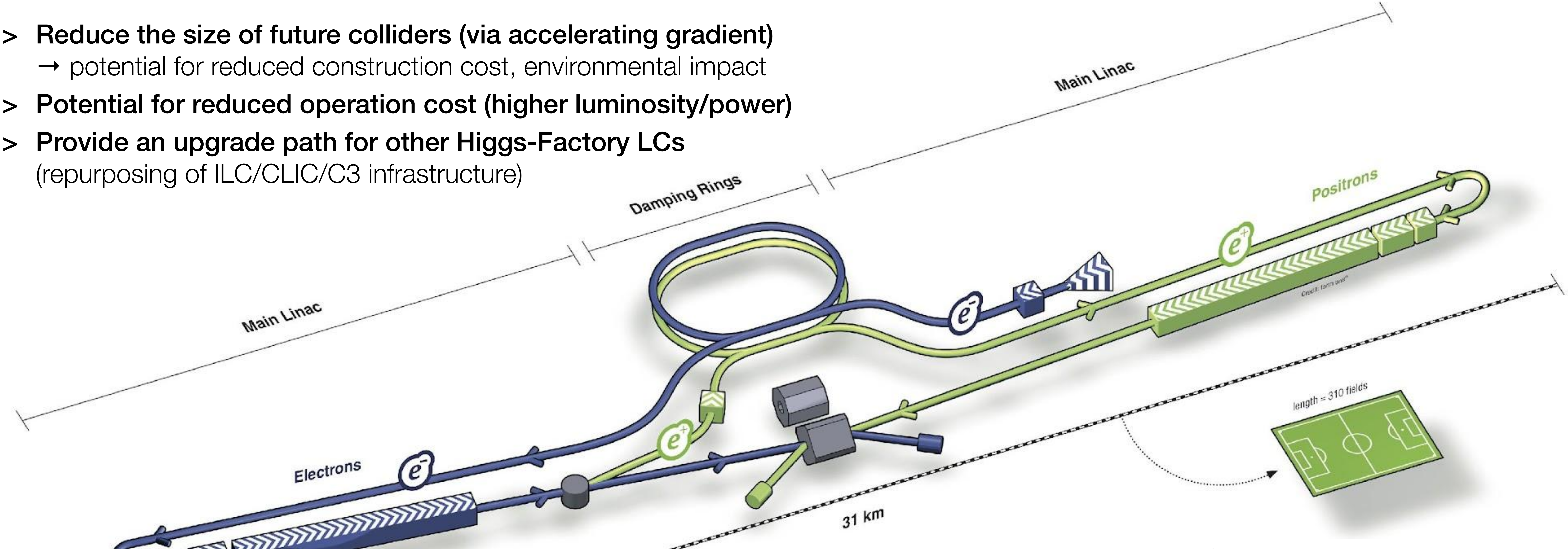
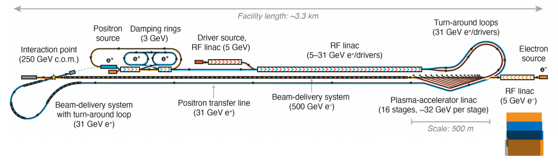
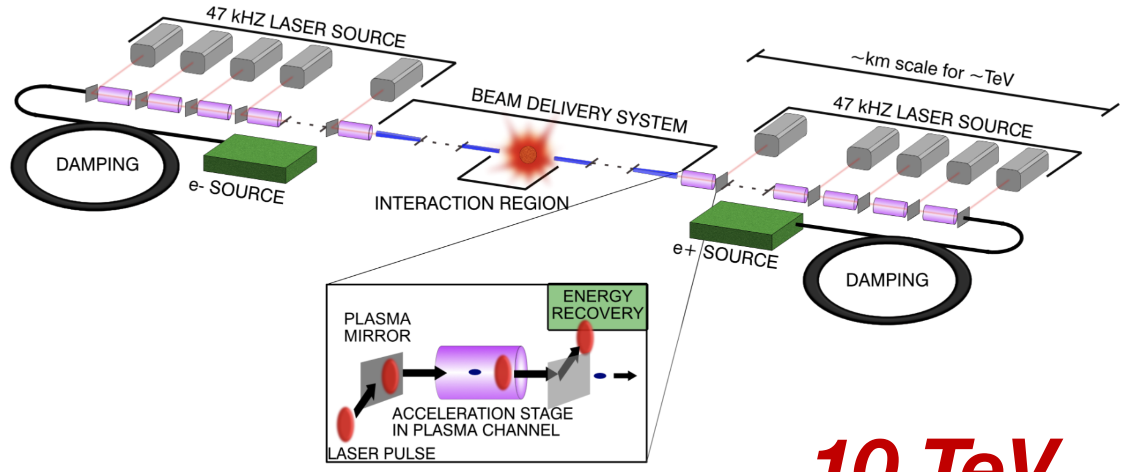






ILC / 500 GeV / 31 km

HALHF / 250 GeV / 3.3 km

Foster, D'Arcy, and Lindstrøm, **NJP** 25, 093037 (2023)

10 TeV

Energy Frontier Collider ~~/ 15 TeV~~ / 6.6 km*

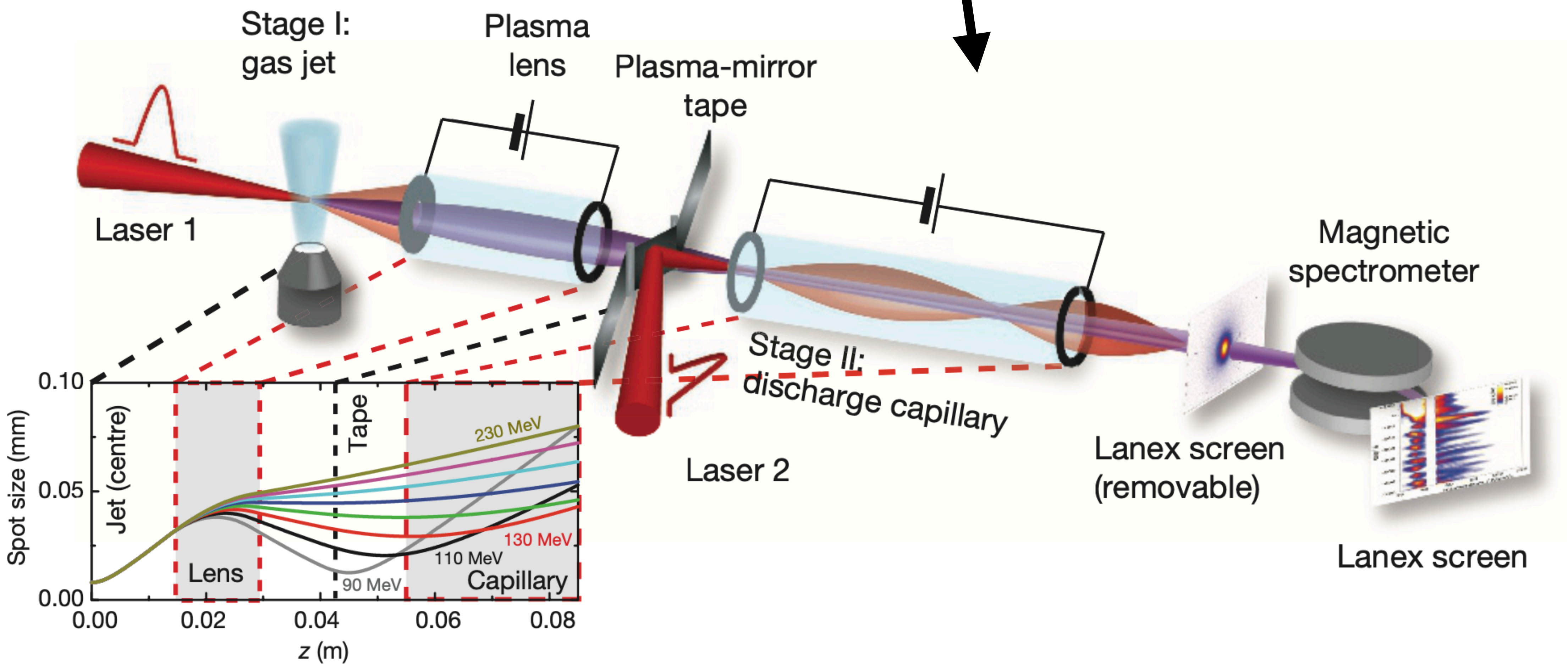
C.B. Schroeder *et al.*, **JINST** 18 T06001 (2023)

*for the linac, not including the BDS

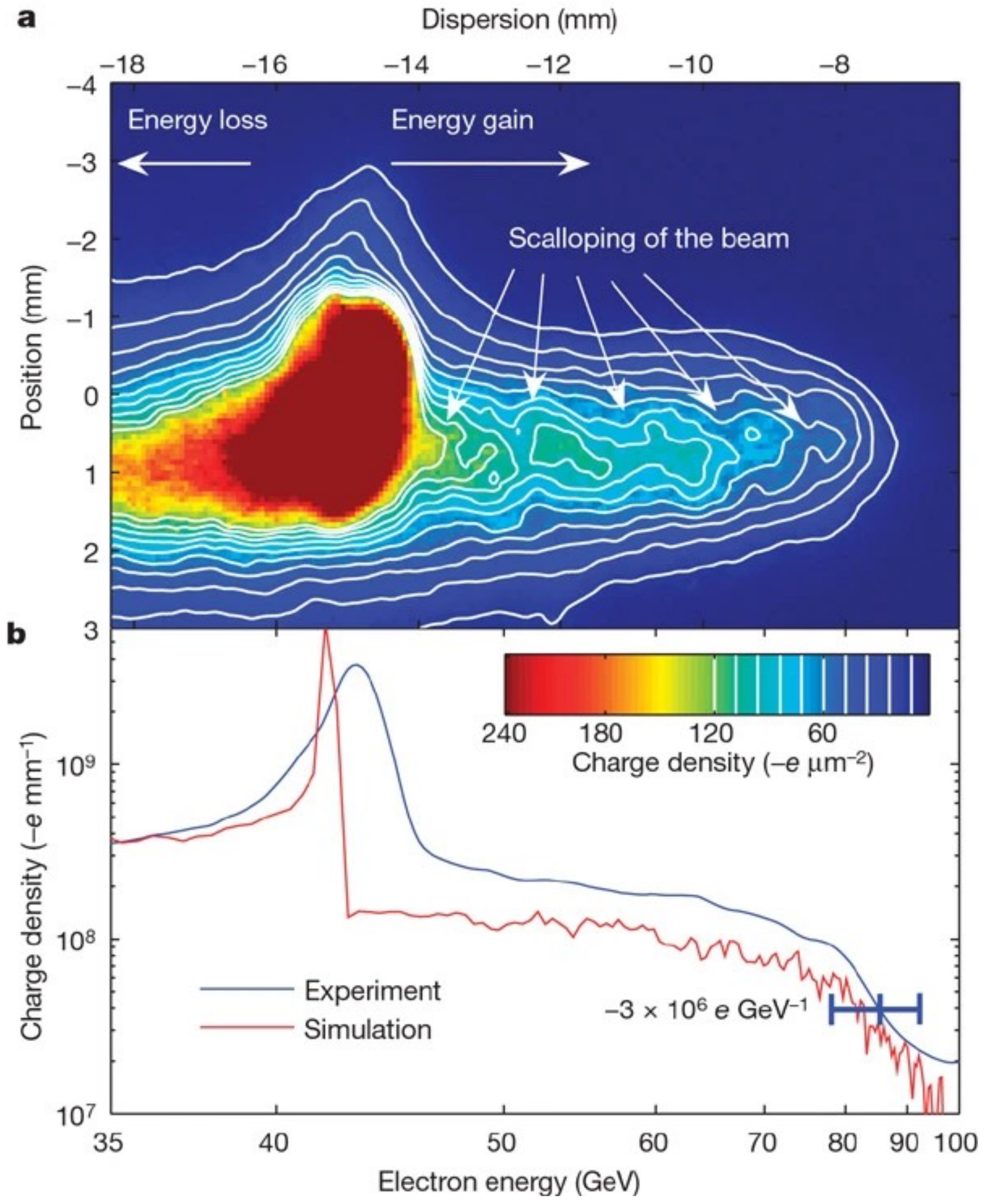
Proof-of-principle progress towards collider readiness

Systematically ticking off the R&D requirements for a collider

- *Towards high energy:*
  - Large energy gain in a single plasma module
  - Staging of two plasma modules



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



From: Blumenfeld et al., Nature 445, 741 (2007)

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- *Towards high beam quality (**luminosity**):*
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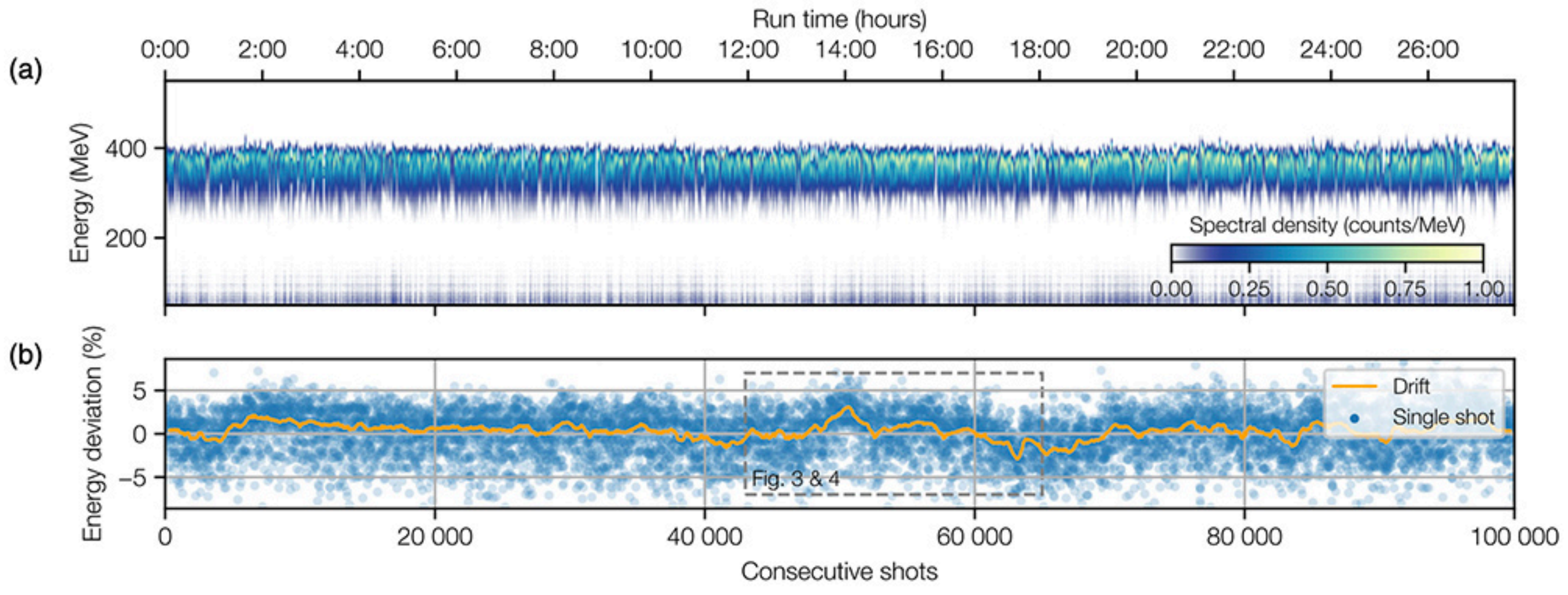
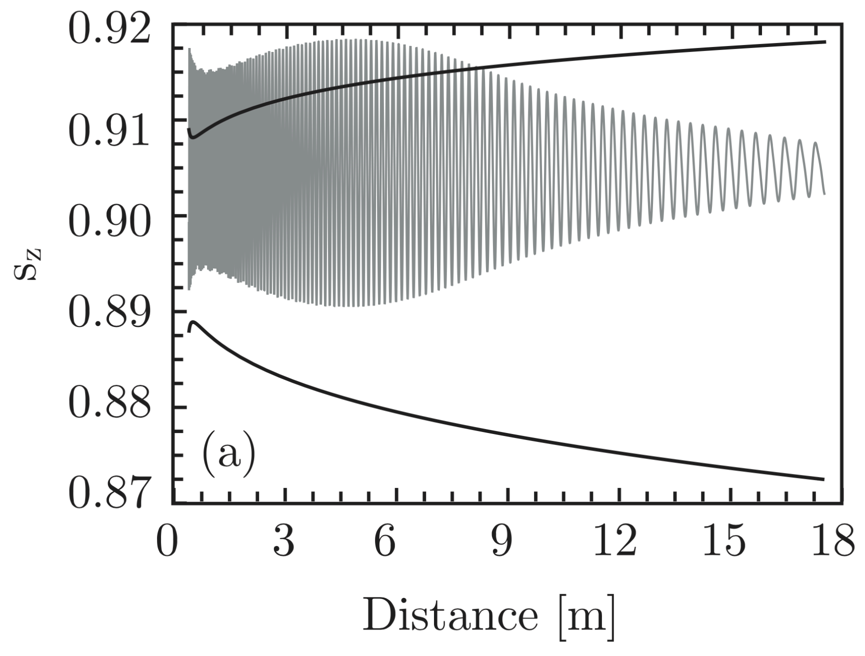
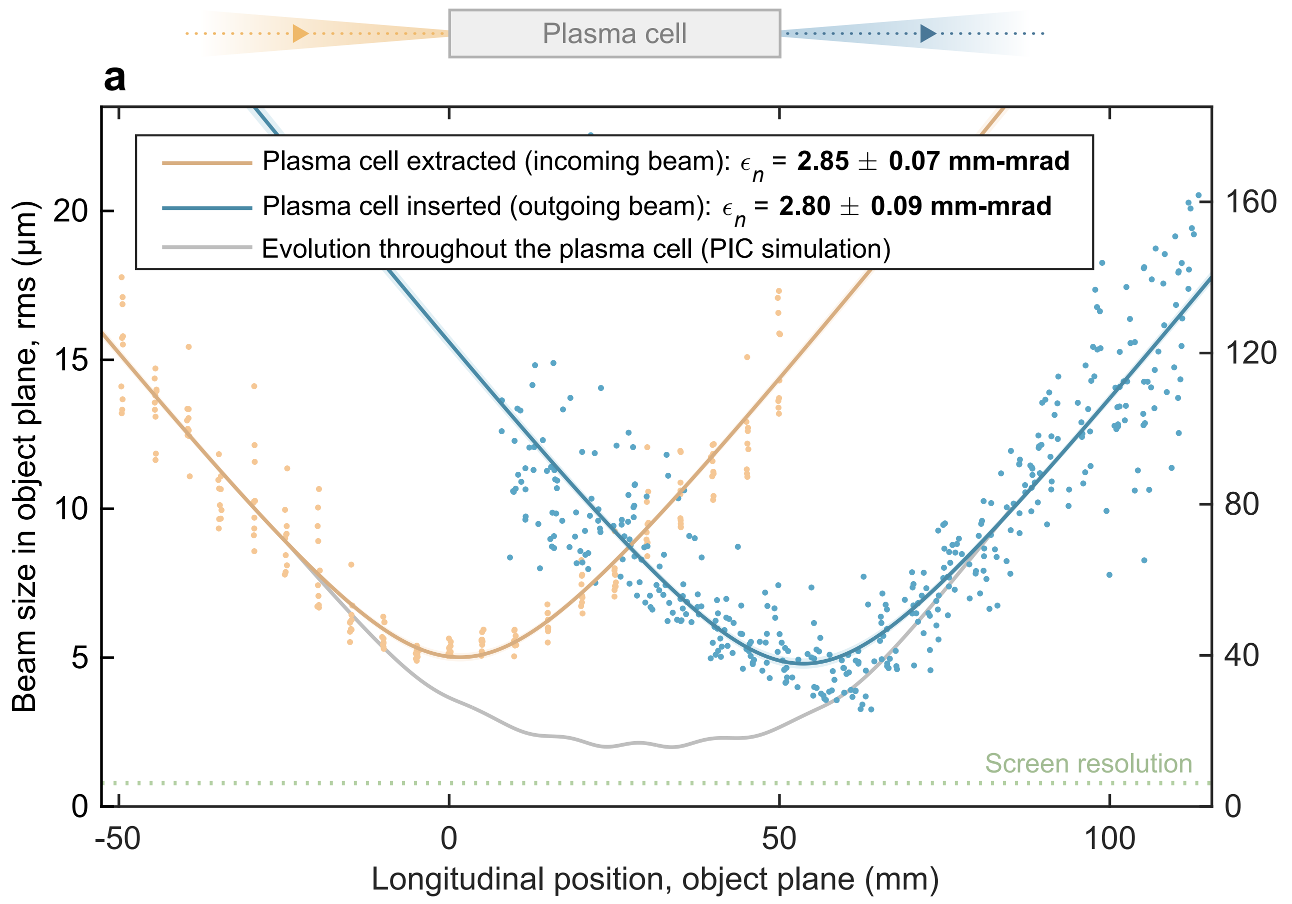
  - Emittance and energy-spread preservation
  - Spin-polarisation preservation



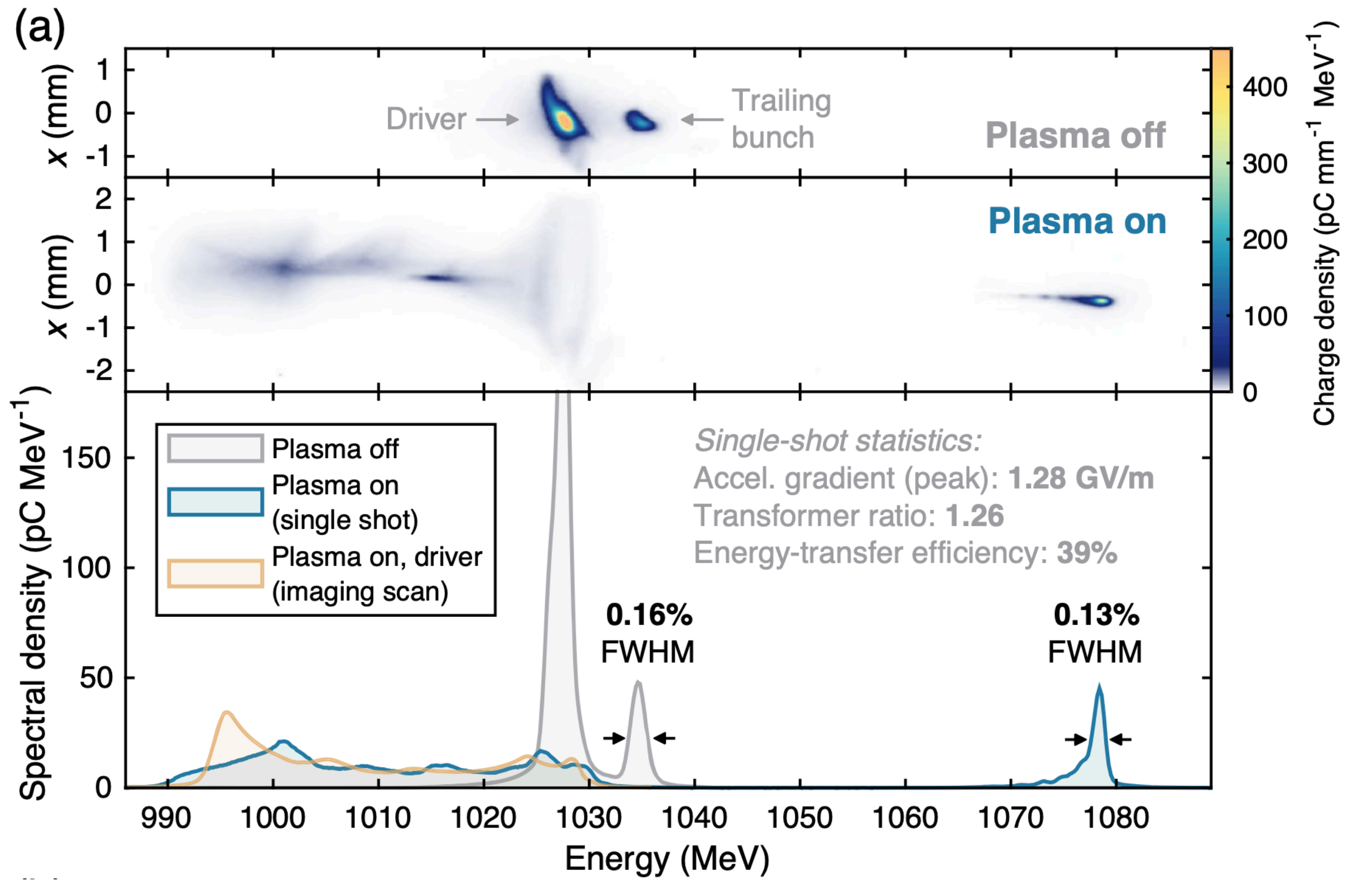
From: Maier et al., Phys. Rev. X 10, 031039 (2020)



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



From: Lindstrøm et al., Nat. Commun. 15, 6097 (2024)



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

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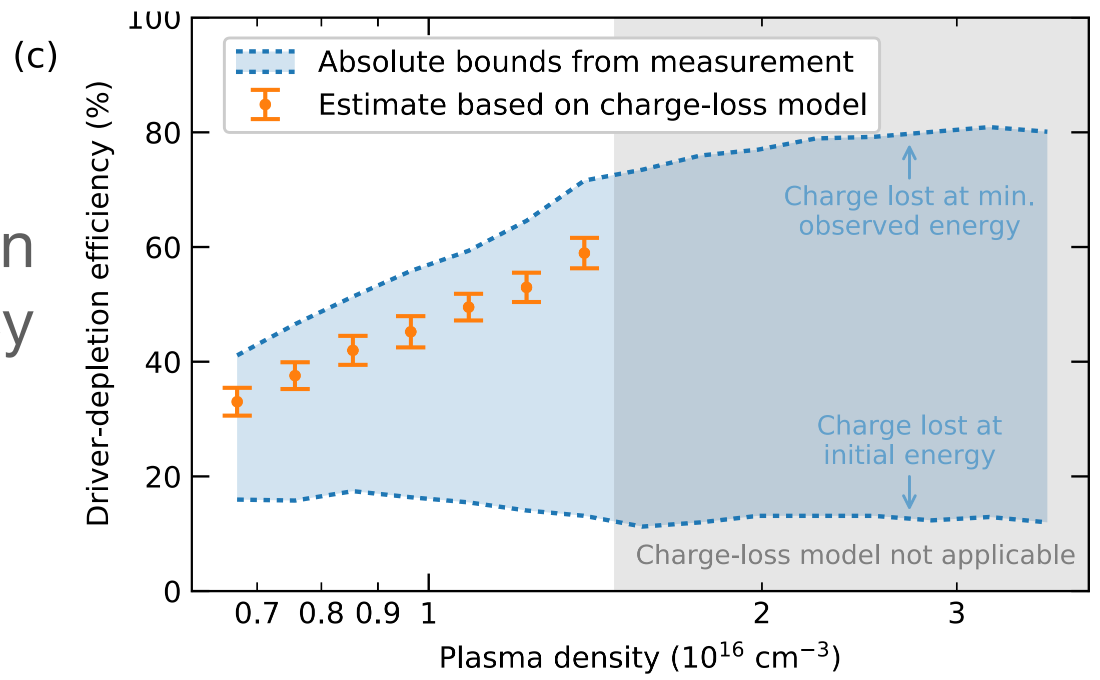
- *Towards high beam quality (**luminosity**):*
  - Transverse and longitudinal stability
  - Emittance and energy-spread preservation
  - Spin-polarisation preservation
- *Towards high beam power (**luminosity**):*
  - High-overall efficiency (wall-plug to beam)
  - Repetition rate
  - Plasma-cell cooling

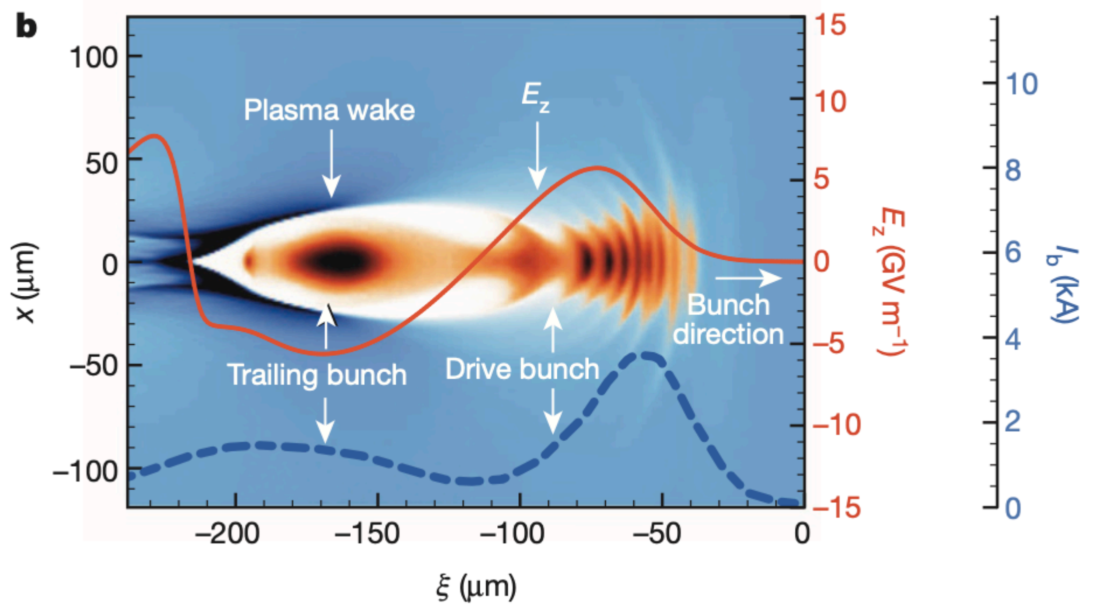
Depletion efficiency



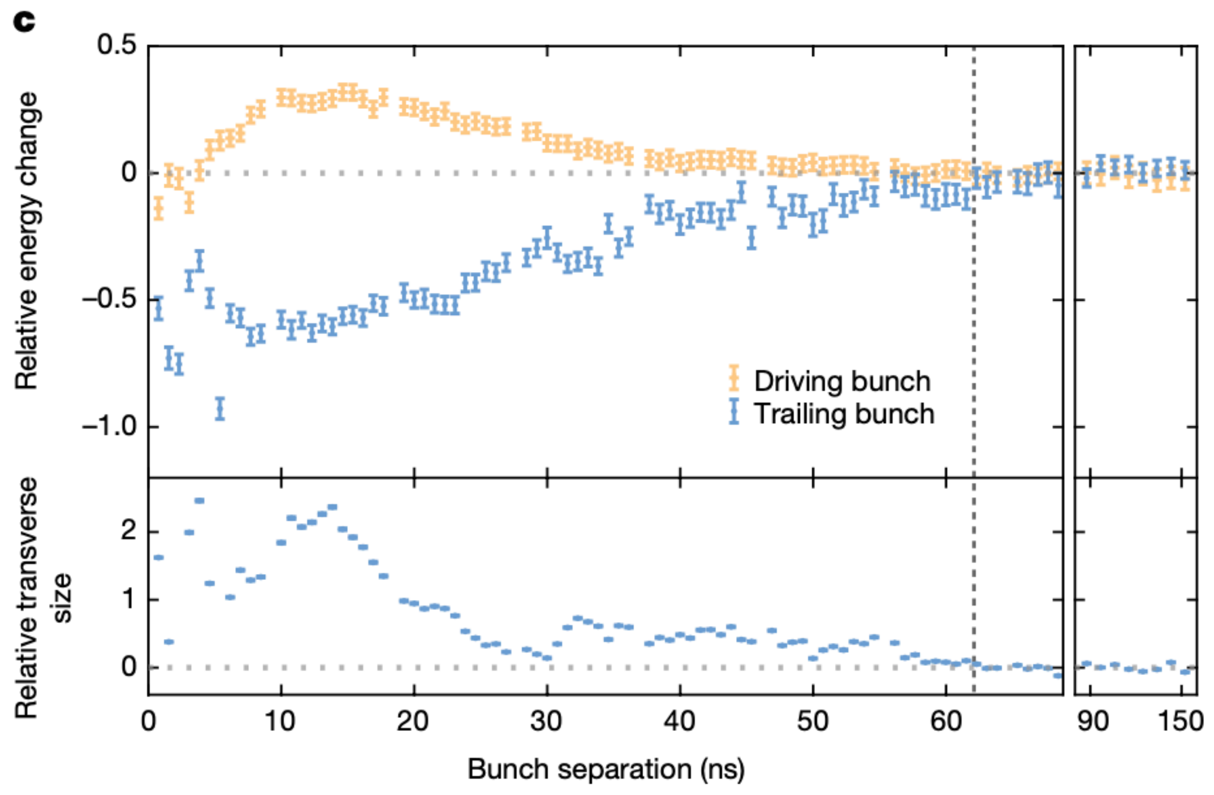
From: Peña et al. PRR (accepted)

(Must be achieved simultaneously)

Extraction efficiency



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

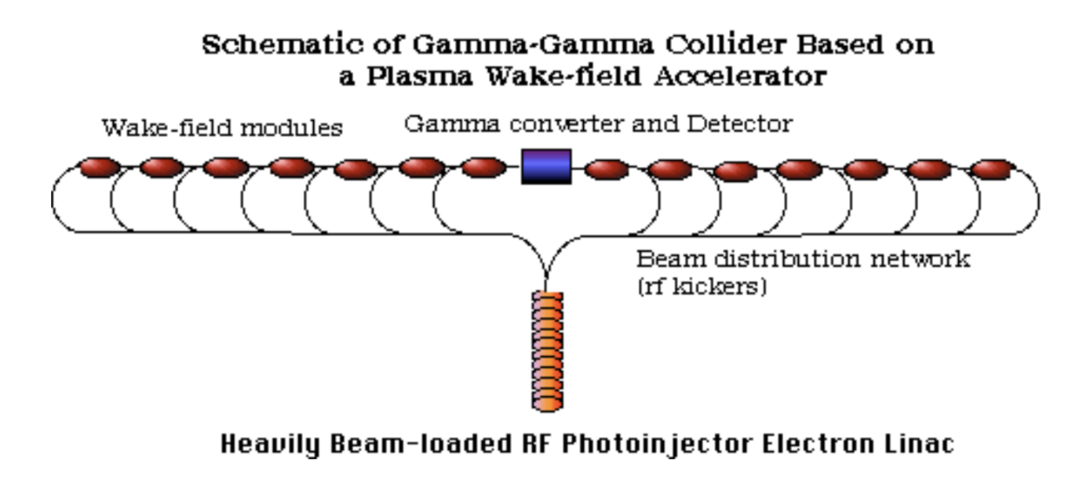


From: D'Arcy et al., Nature 603, 58 (2022)

Significant experimental progress motivates consideration for HEP

Straw-person designs have been a useful exercise to guide R&D over the last decades

Rosenzweig, Snowmass **1996**


Schematic of Gamma-Gamma Collider Based on a Plasma Wake-field Accelerator

Seryi, PAC **2009**

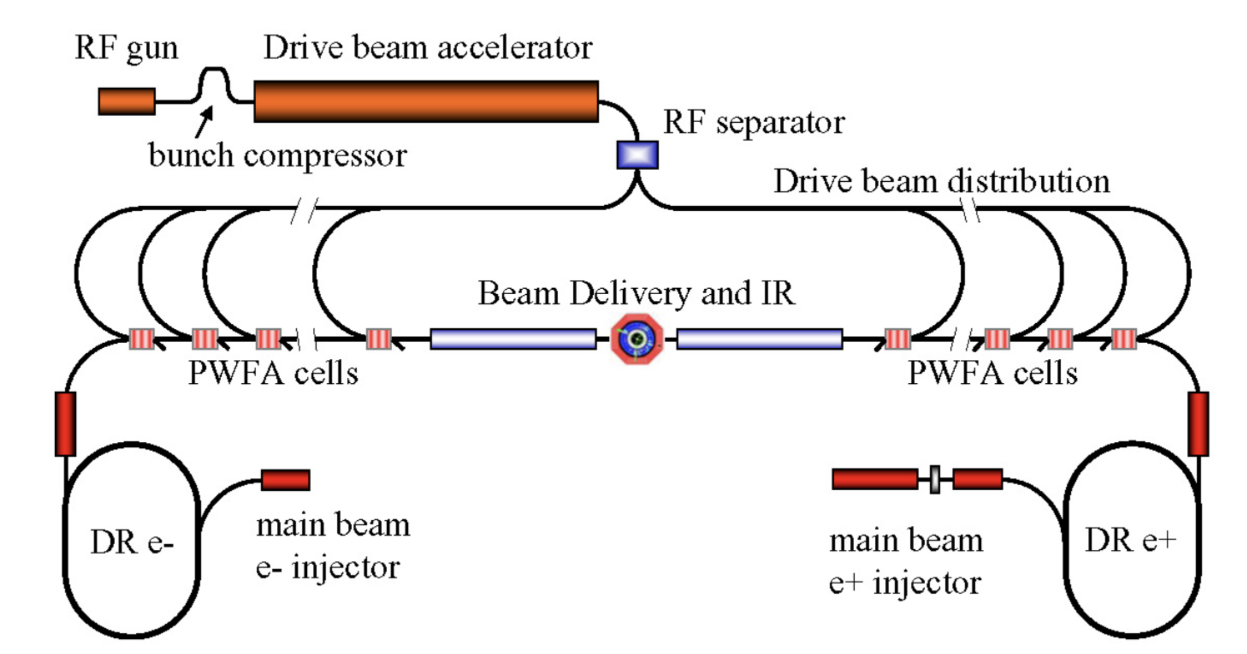
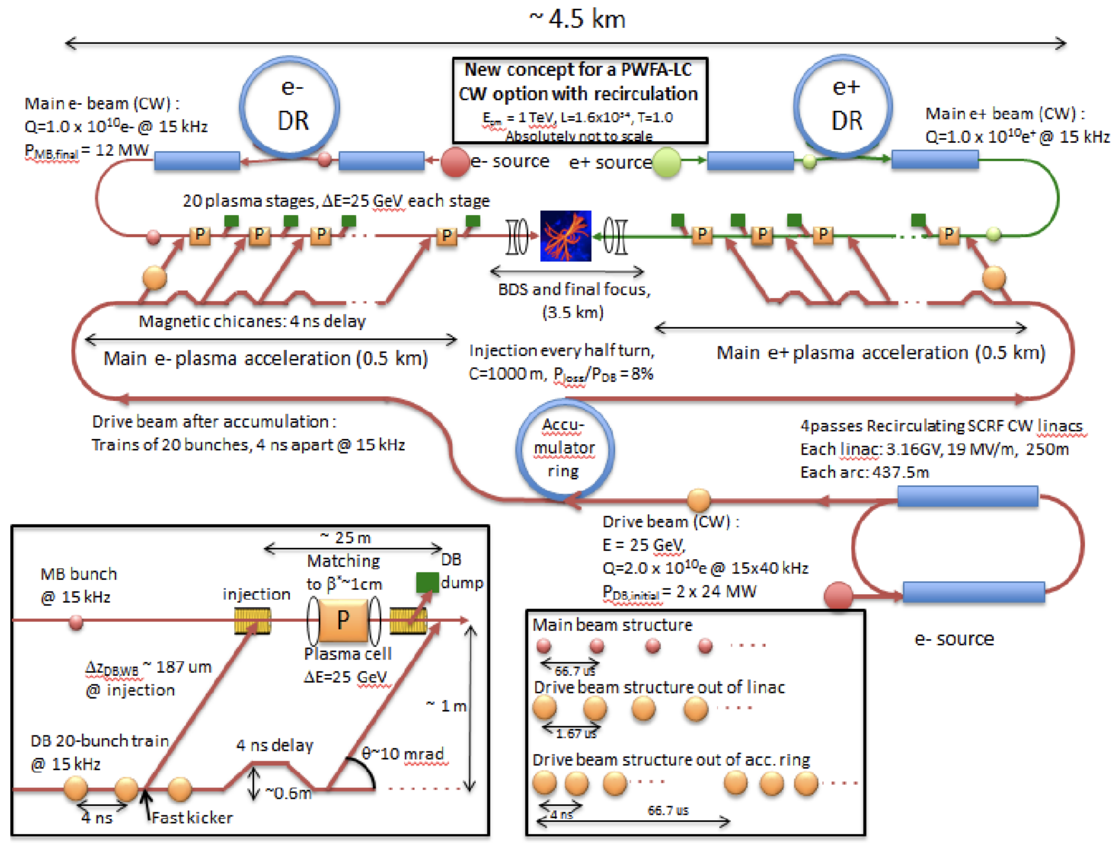


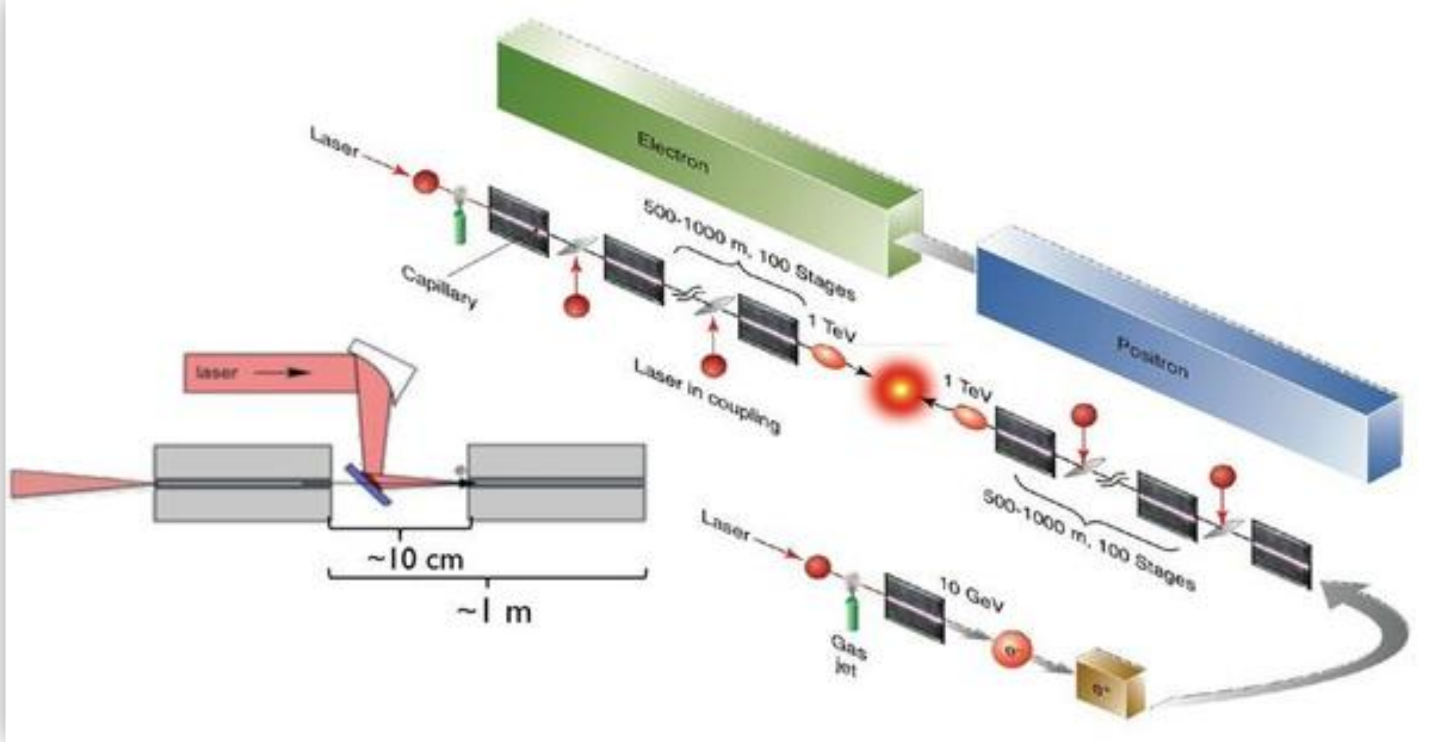
Figure 1: Concept for a multi-stage PWFA-based Linear Collider.

Adli, Snowmass **2013**

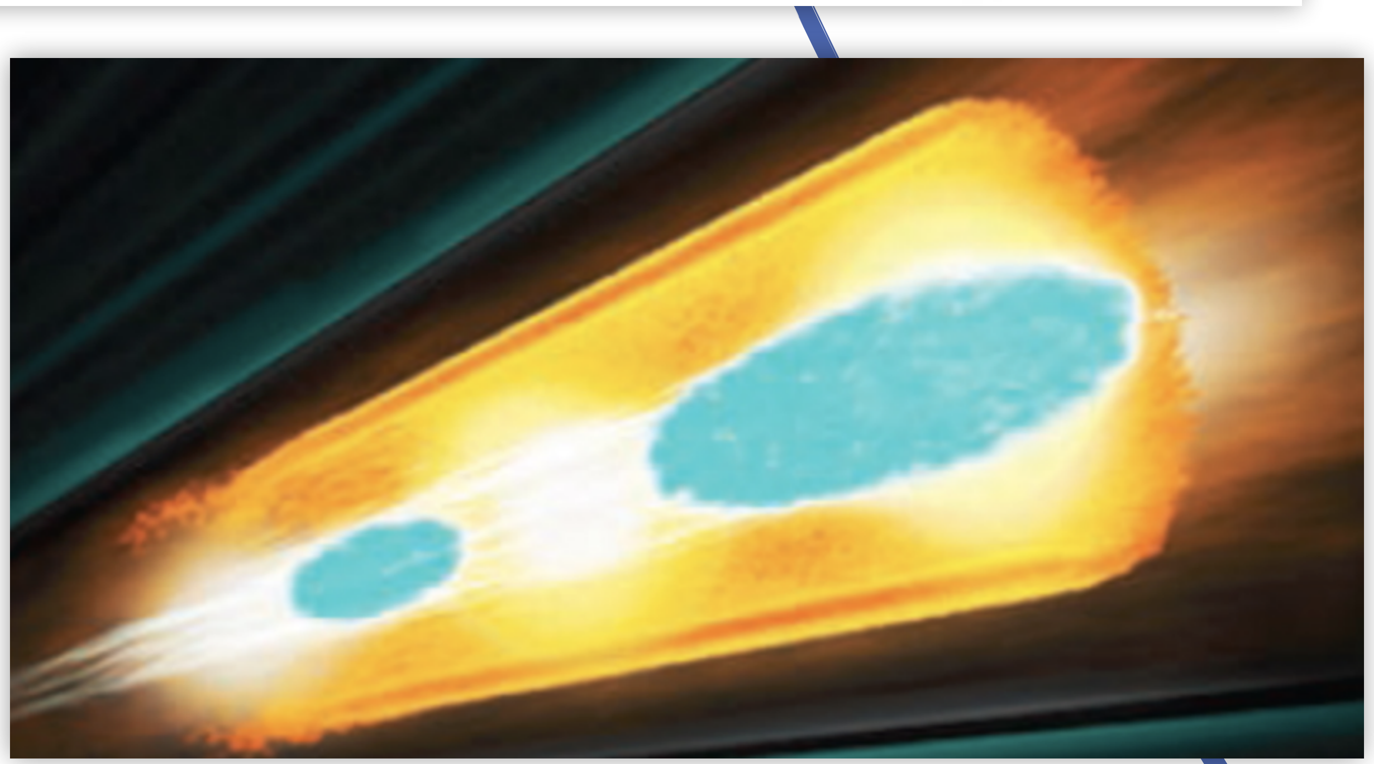
Figure 1: Layout of a 1 TeV PWFA Linear Collider



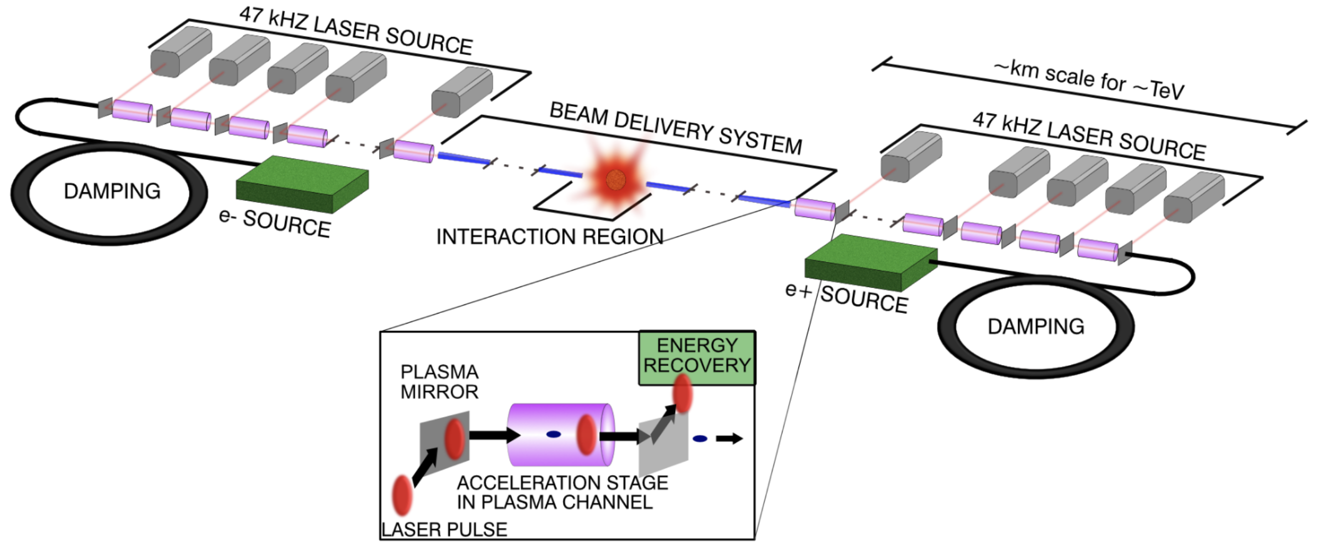
Leemans, Physics Today **2009**



Schroeder, NIM A **2016**



Schroeder, JINST **2023**



increasing realism/ complexity

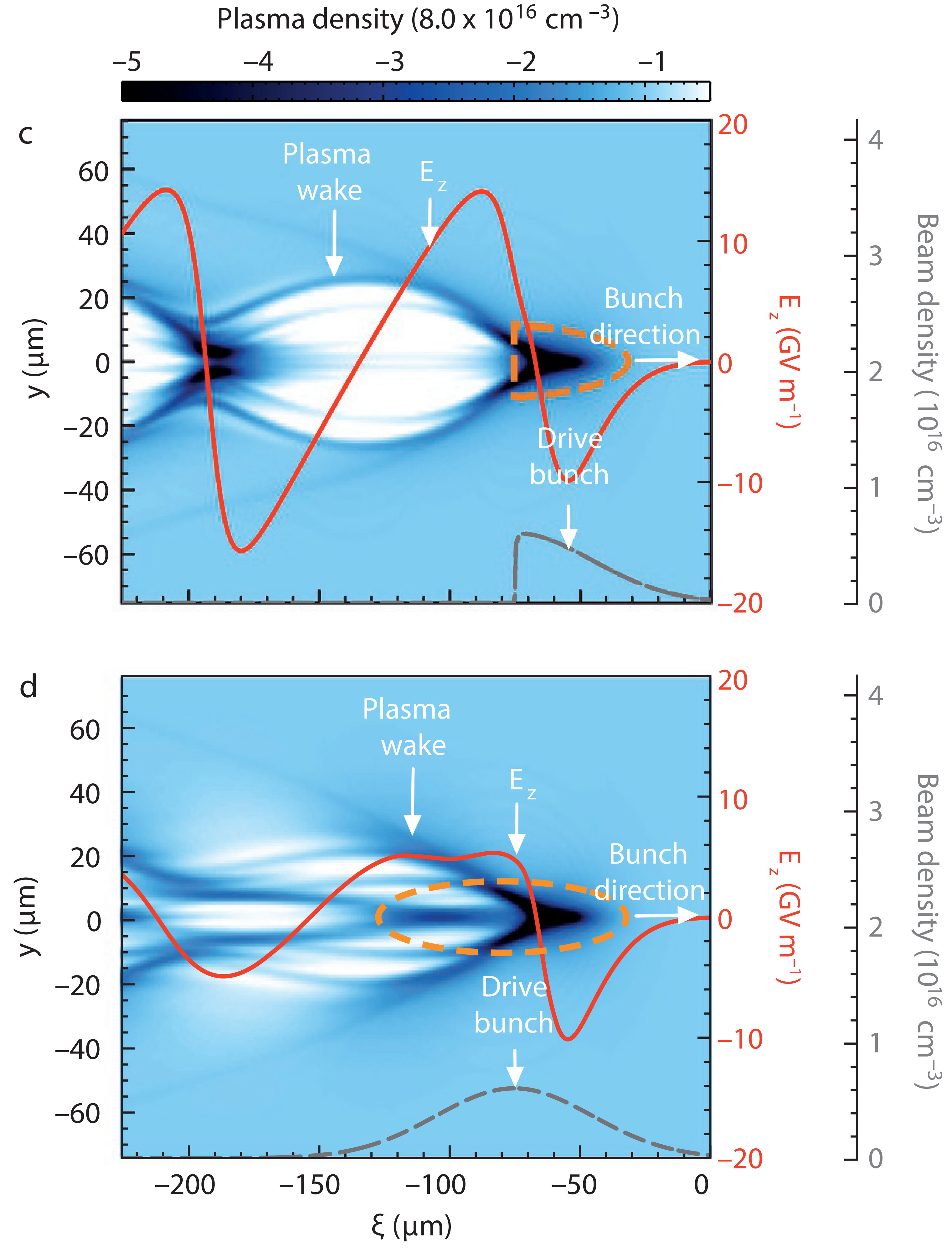
Beam-driven

Laser-driven

One key stumbling block in each concept: *positron acceleration*

The positron challenge is created by charge asymmetry (high mobility of light plasma electrons vs. heavier ions)

- Positron acceleration has been demonstrated
  - Several schemes proposed to improve beam quality — but lack of e^+ test facilities
- Positron acceleration in plasma lags behind electron acceleration
  - 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)



Source: Corde et al. Nature 524, 442 (2015).

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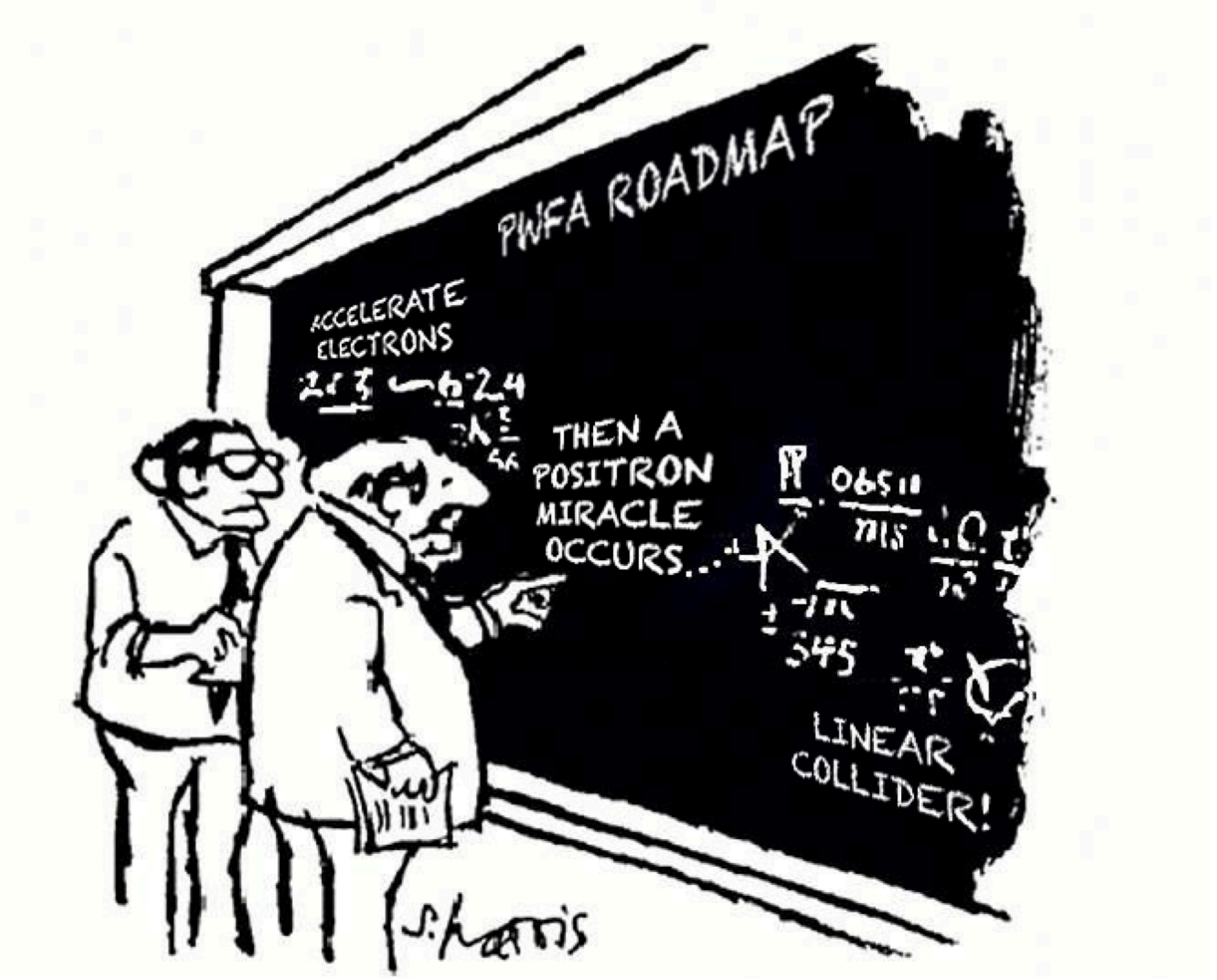


Adopted from S. Harris and C. Lindstrøm

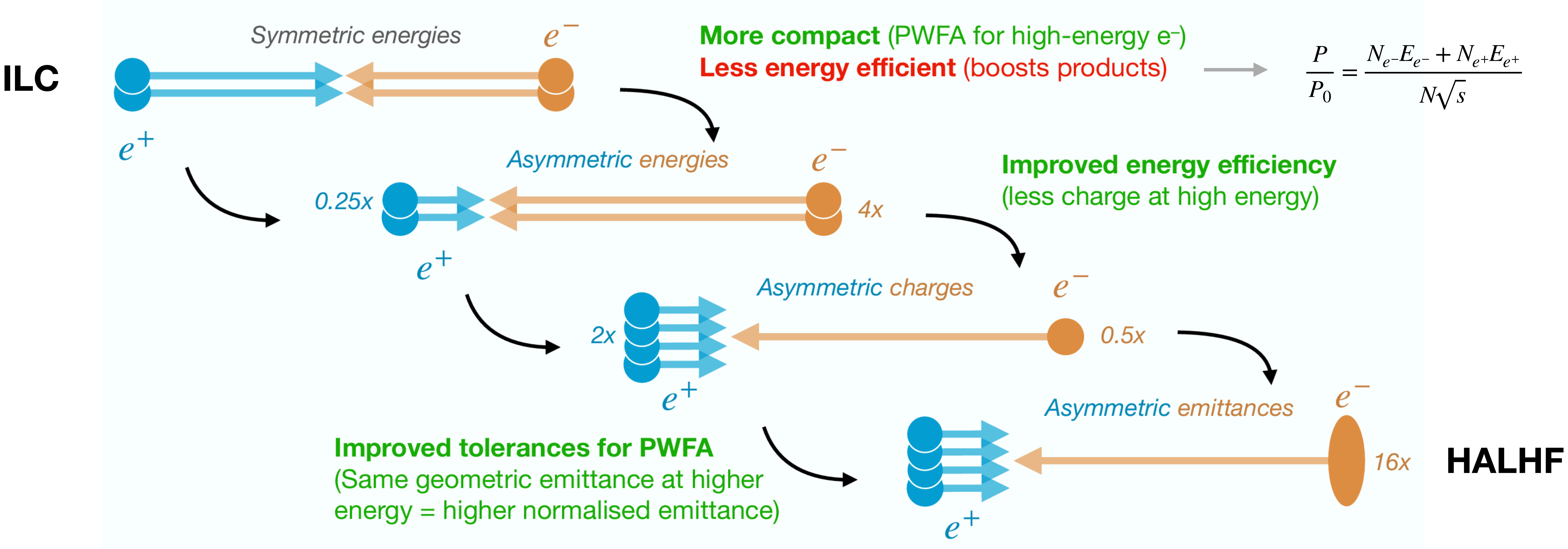
The pragmatic approach:

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

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

Question: Can asymmetries reduce facility cost / increase feasibility?

In fact… the more asymmetries, the better!



More compact (PWFA for high-energy e⁻)

Less energy efficient (boosts products)

$$\frac{P}{P_0} = \frac{N_{e^-}E_{e^-} + N_{e^+}E_{e^+}}{N\sqrt{s}}$$

Improved energy efficiency
(less charge at high energy)

Improved tolerances for PWFA
(Same geometric emittance at higher energy = higher normalised emittance)

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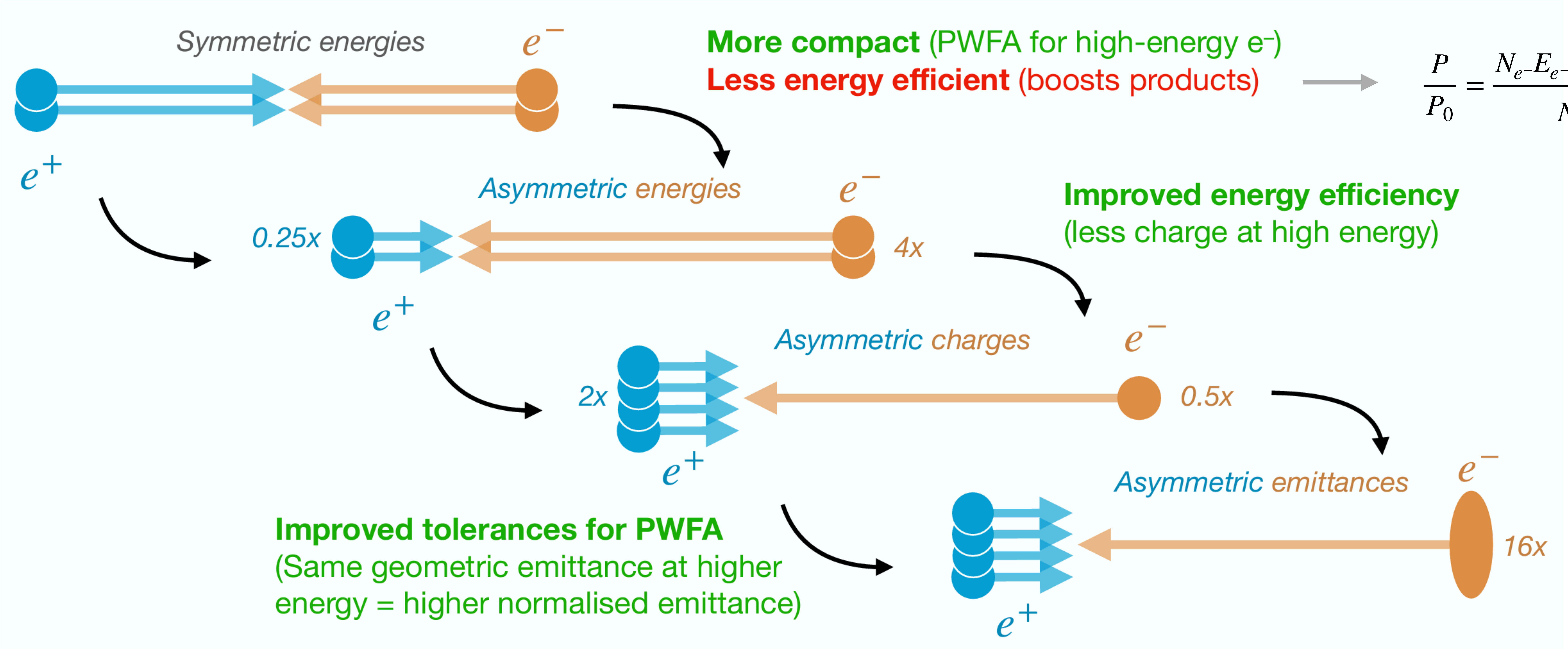
ILC



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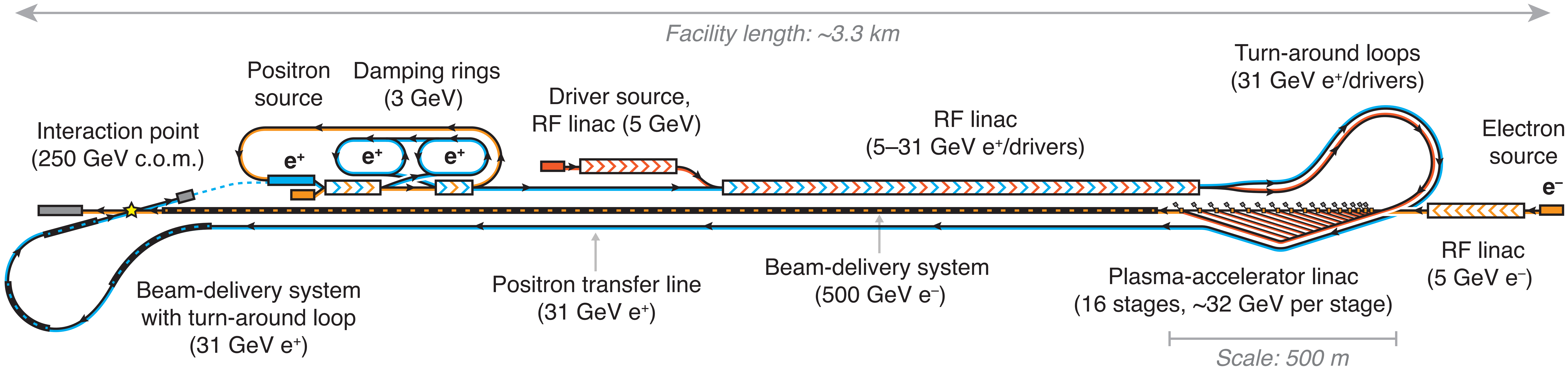
HALHF

	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
ILC:	125 / 125	300 / 300	2 / 2	10 / 10	35 / 35	13 / 13	0.41 / 0.41	1.12	0.92	1
HALHF:	31.3 / 500	75 / 75	4 / 1	10 / 40	35 / 140	3.3 / 13	0.10 / 0.41	1.01	0.58	1.25

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory

Utilising plasma technology for a compact and cost-effective Higgs factory



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

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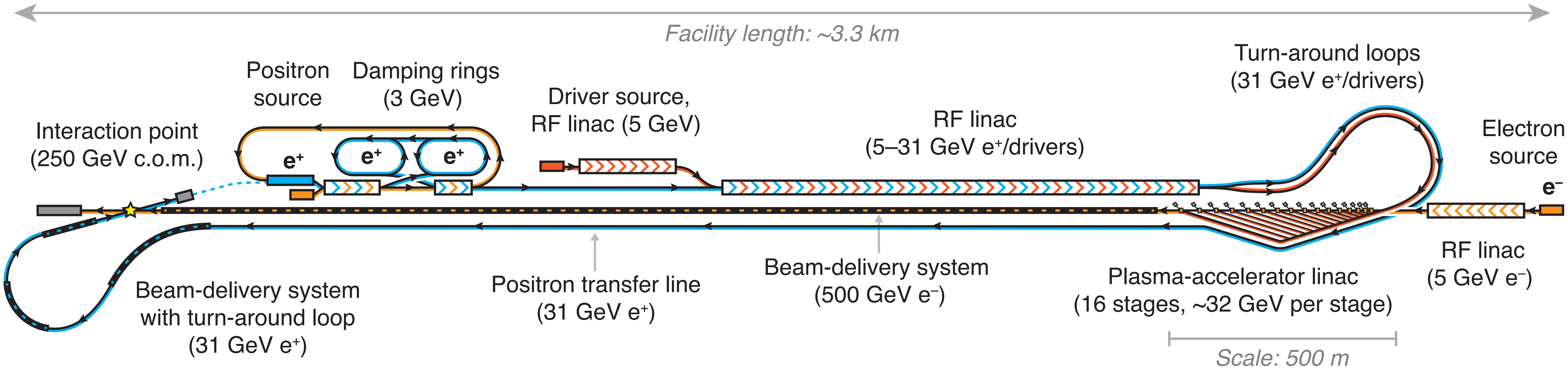

Source: Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

- ***Beam-driven***: Use e^+ RF linac for accelerating e^- drivers (dual-purpose)
- ***Overall footprint***: ~3.3 km
  - Length dominated by e^- beam-delivery system
  - Fits in most major particle-physics laboratories
- ***Impact***: potentially 4x cheaper and greener than counterparts based solely on RF

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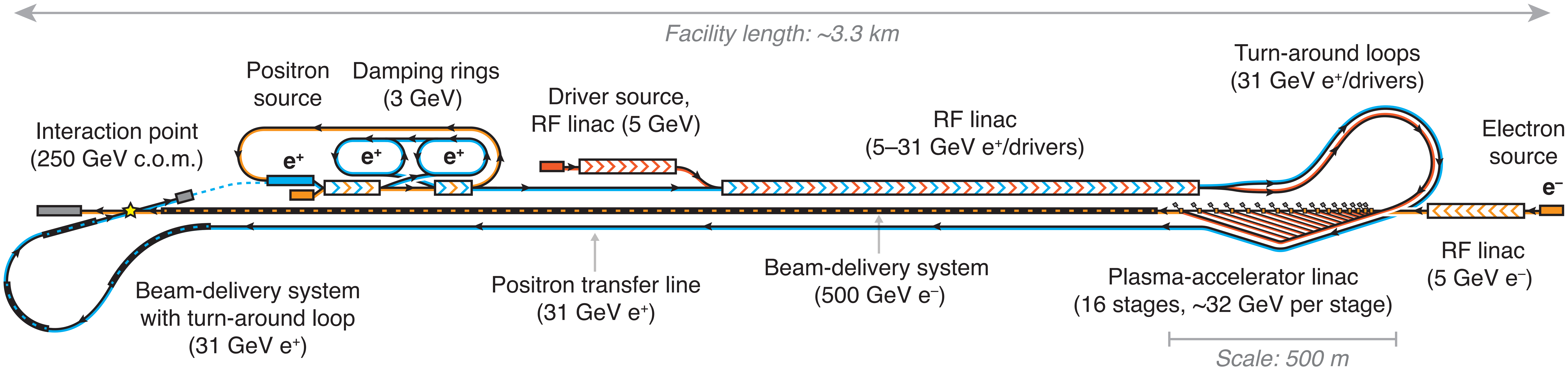

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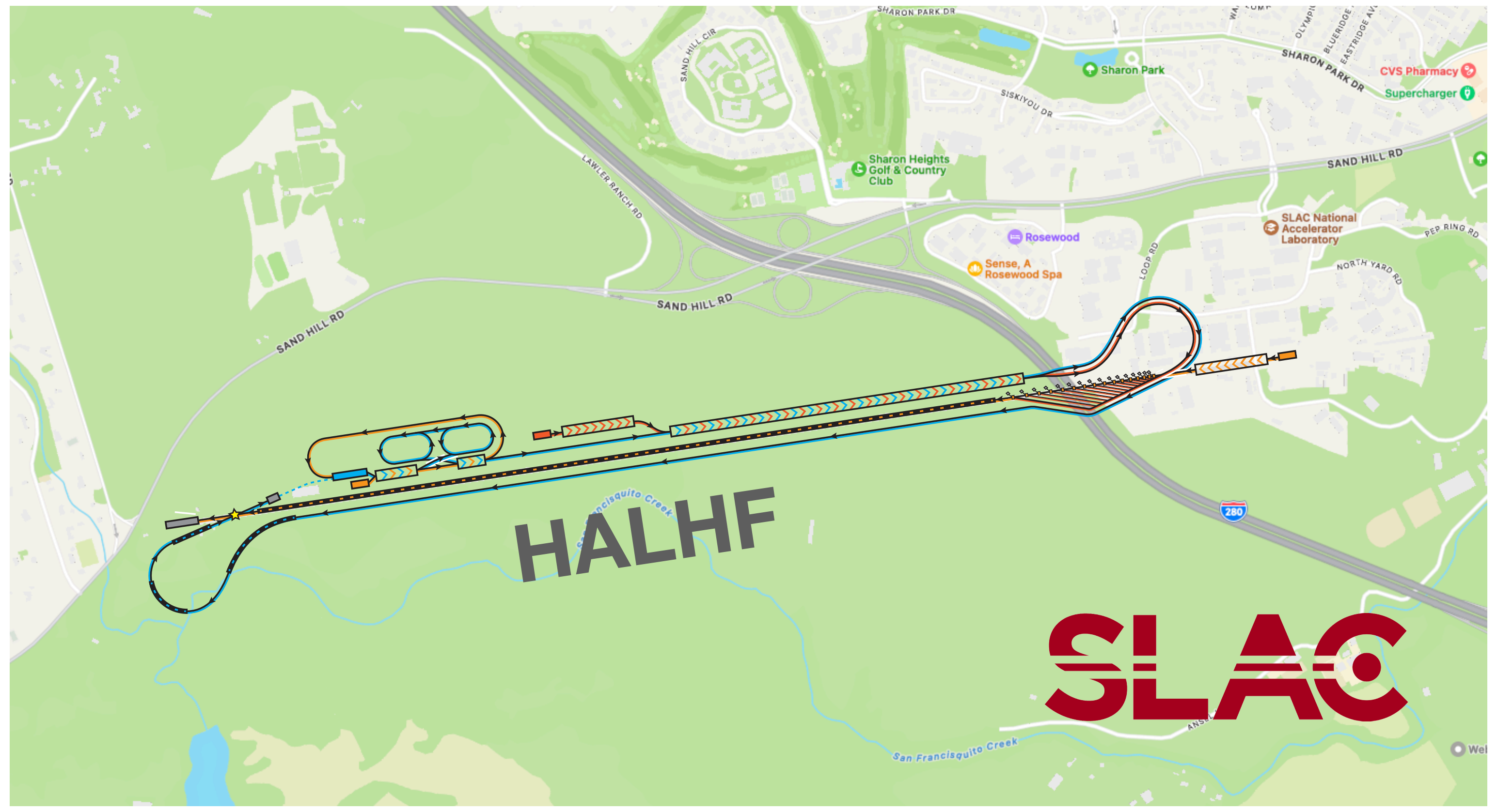
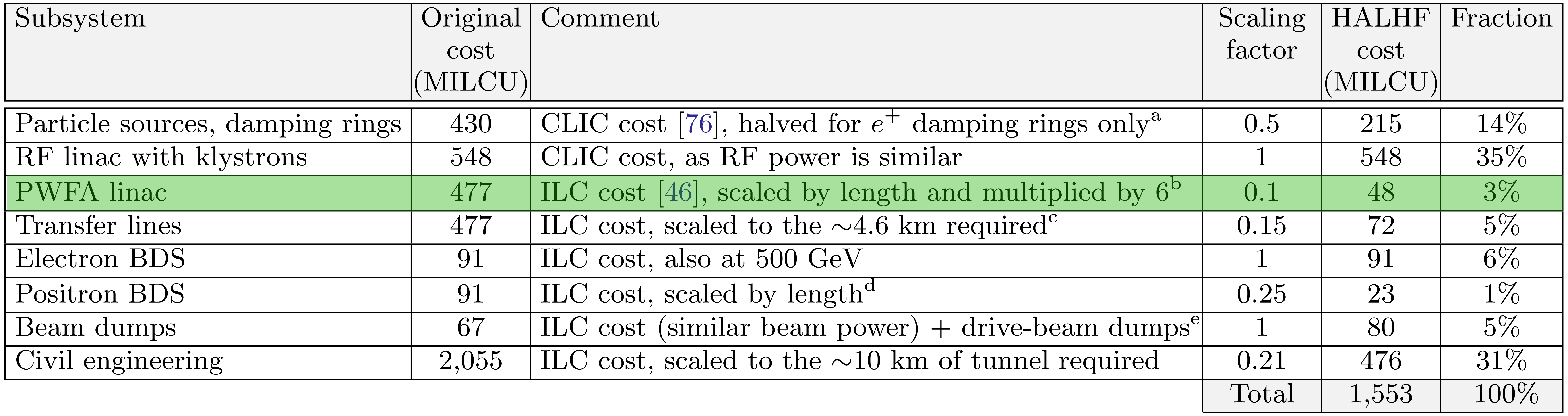


Rough cost estimates for HALHF

- 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 $\sim$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 $\sim$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.

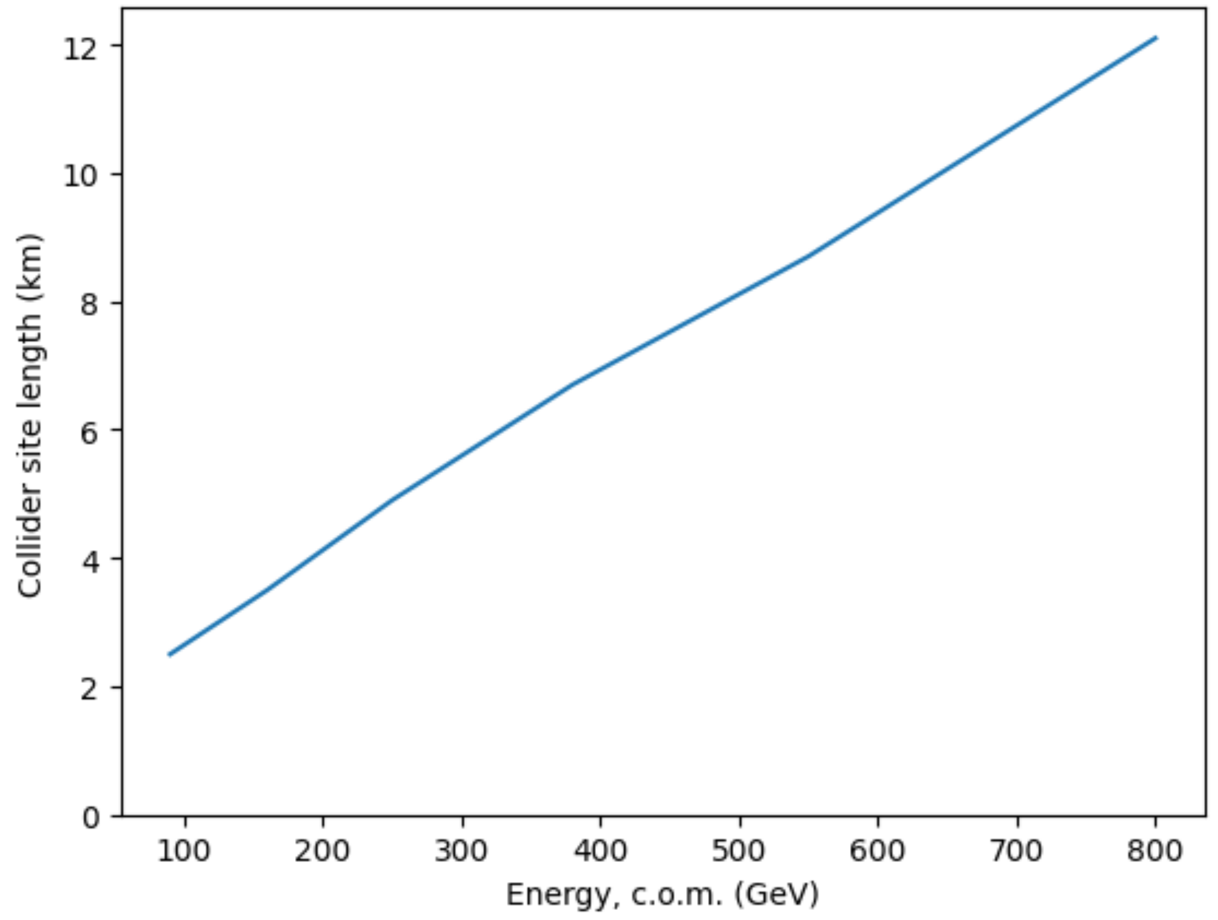
380 GeV, 550 GeV, and beyond?

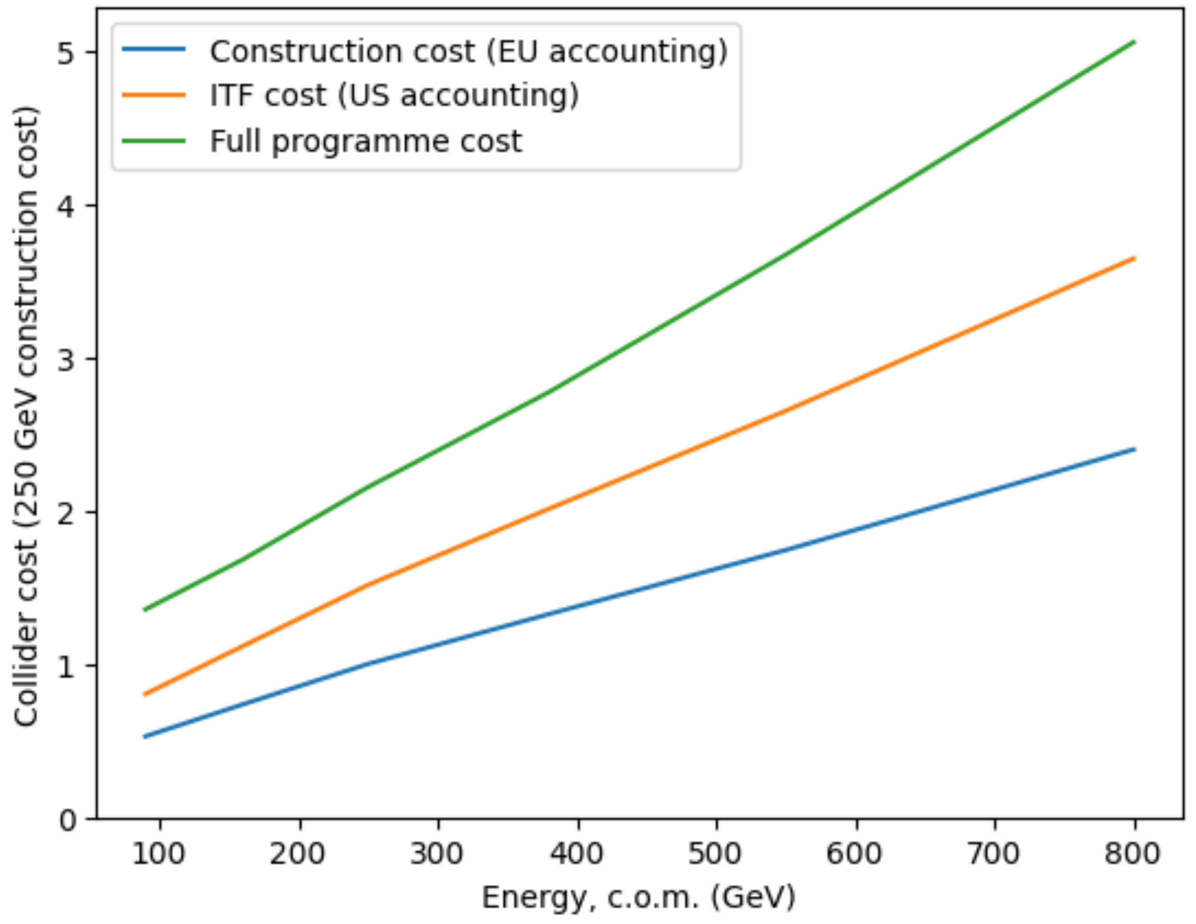
How does the length and cost scale with energy?

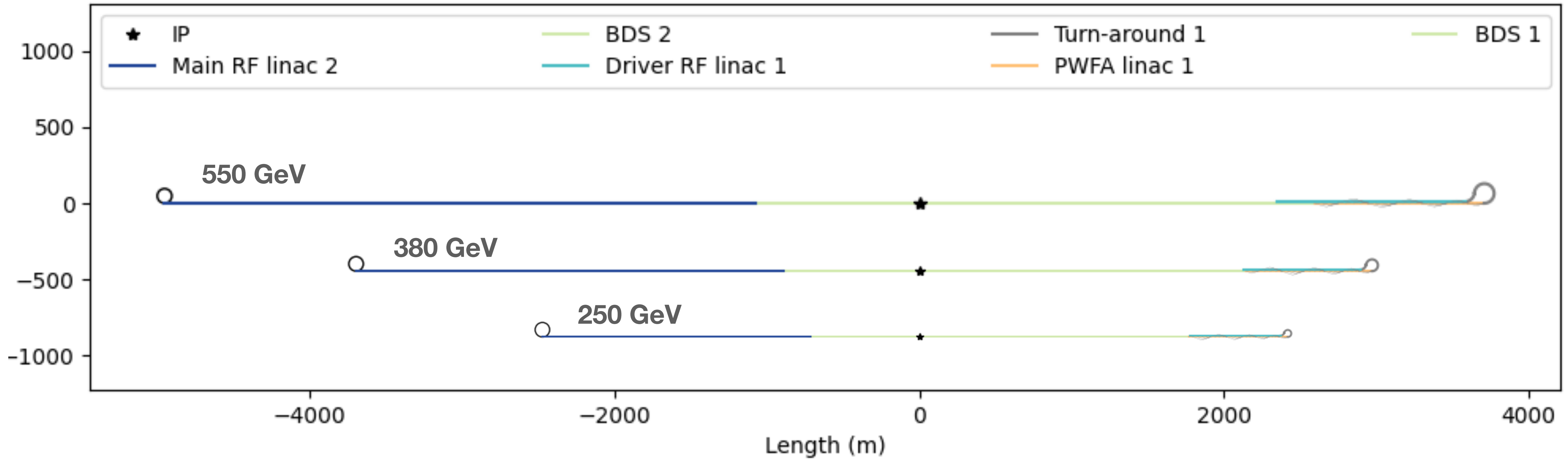
- Higgs-physics motivations for higher energies:

Energy c.o.m. (GeV)	***Length (km)***	***EU / US / Full Programme Cost (norm. cost units)***
250 (HZ)	4.9	1 / 1.5 / 2.2
380 (ttbar)	6.7	1.3 / 2.0 / 2.8
550 (HHH)	8.7	1.7 / 2.7 / 3.7
800	12.1	2.4 / 3.6 / 5.1

Bayesian optimisation framework developed to optimise the footprint for cost (build + run)



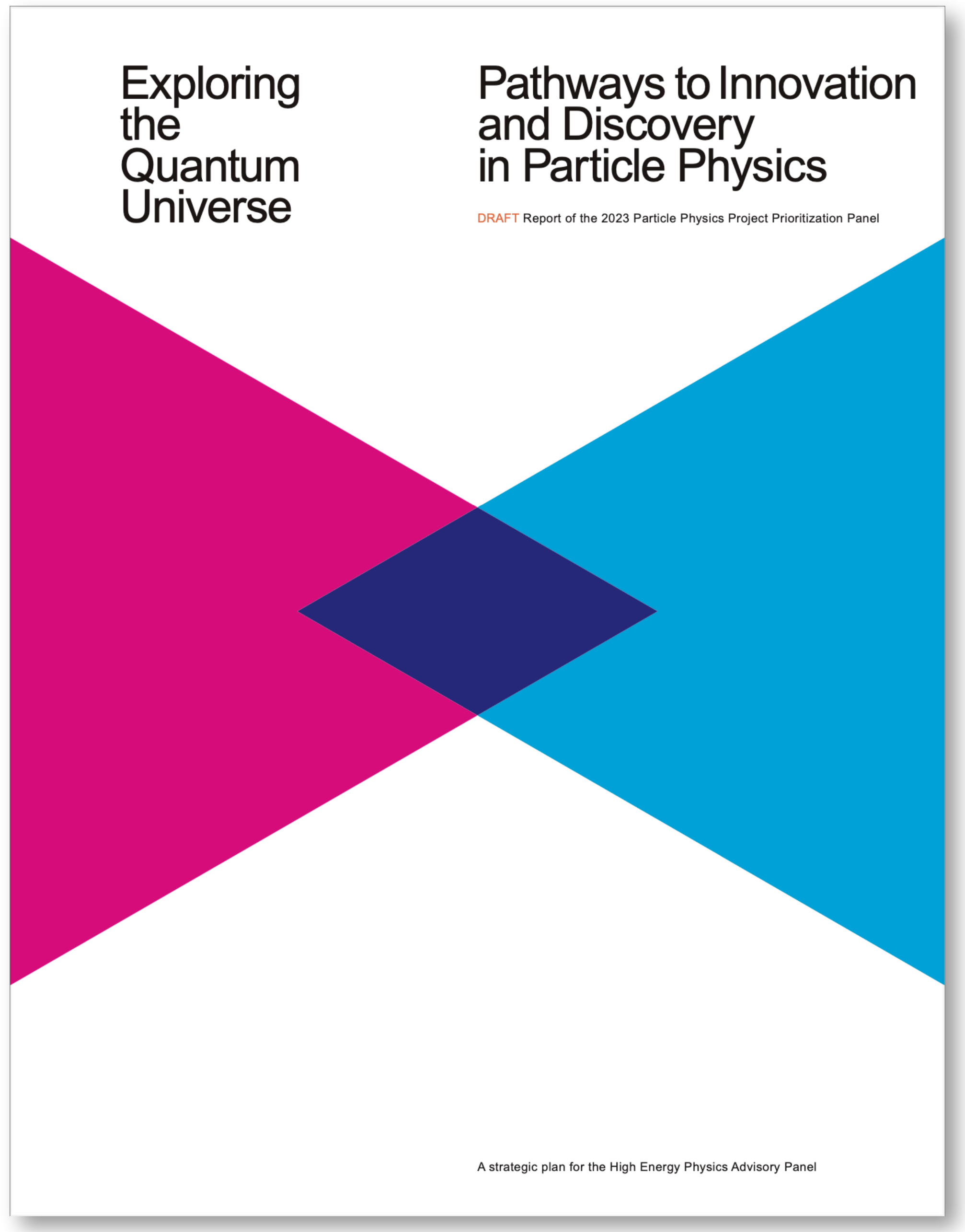




- But HALHF does not scale to the energy frontier ➞ a multi-TeV collider will have to be symmetric again…

10 TeV pCM wakefield collider

P5 prioritises accelerator R&D toward a future 10 TeV pCM collider



Exploring
the
Quantum
Universe

Pathways to Innovation
and Discovery
in Particle Physics

DRAFT Report of the 2023 Particle Physics Project Prioritization Panel

A strategic plan for the High Energy Physics Advisory Panel

Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

Investing in the future of the field to fulfill this vision requires the following:

a. Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years (sections 3.2, 5.1, 6.5 and Recommendation 6).

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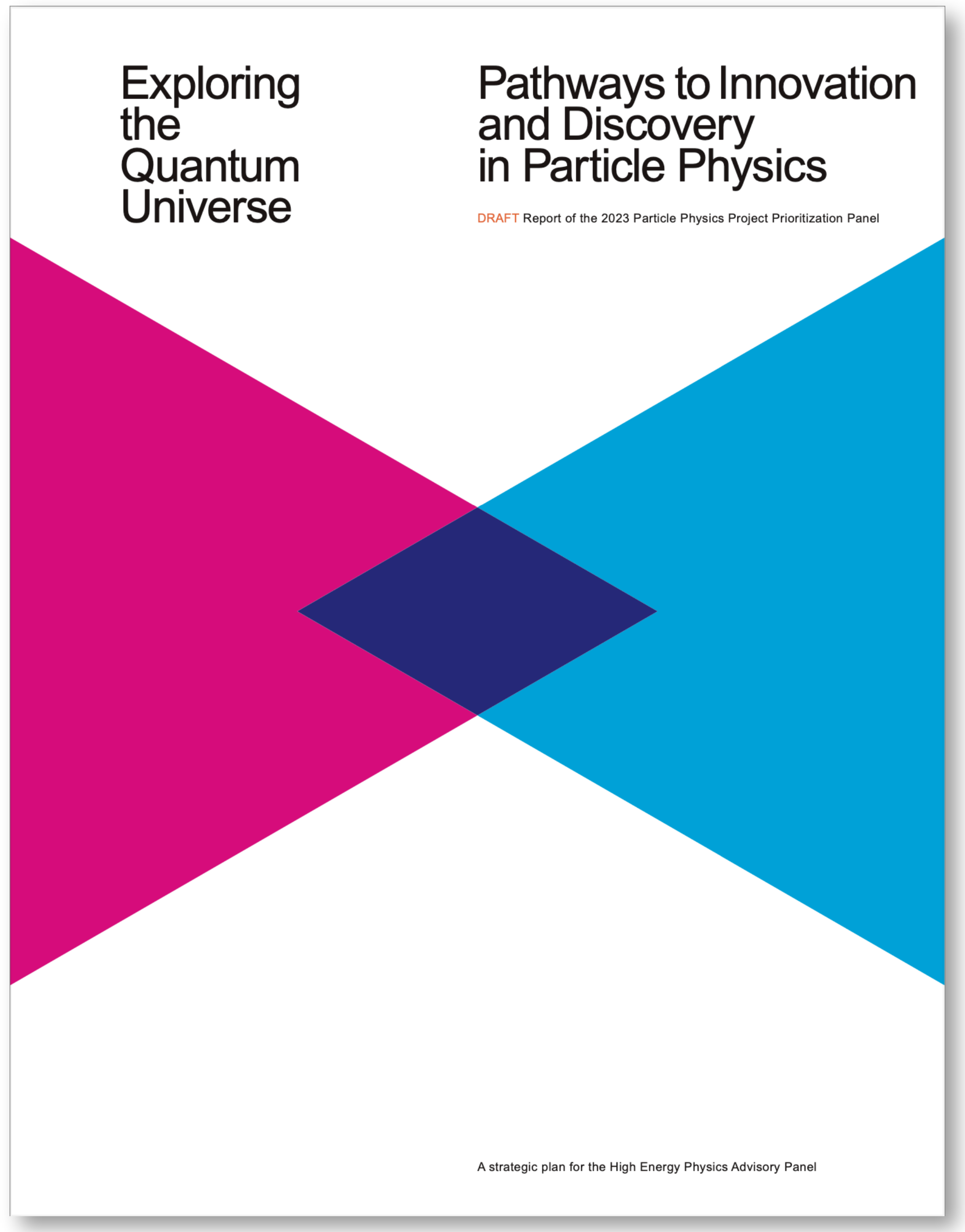

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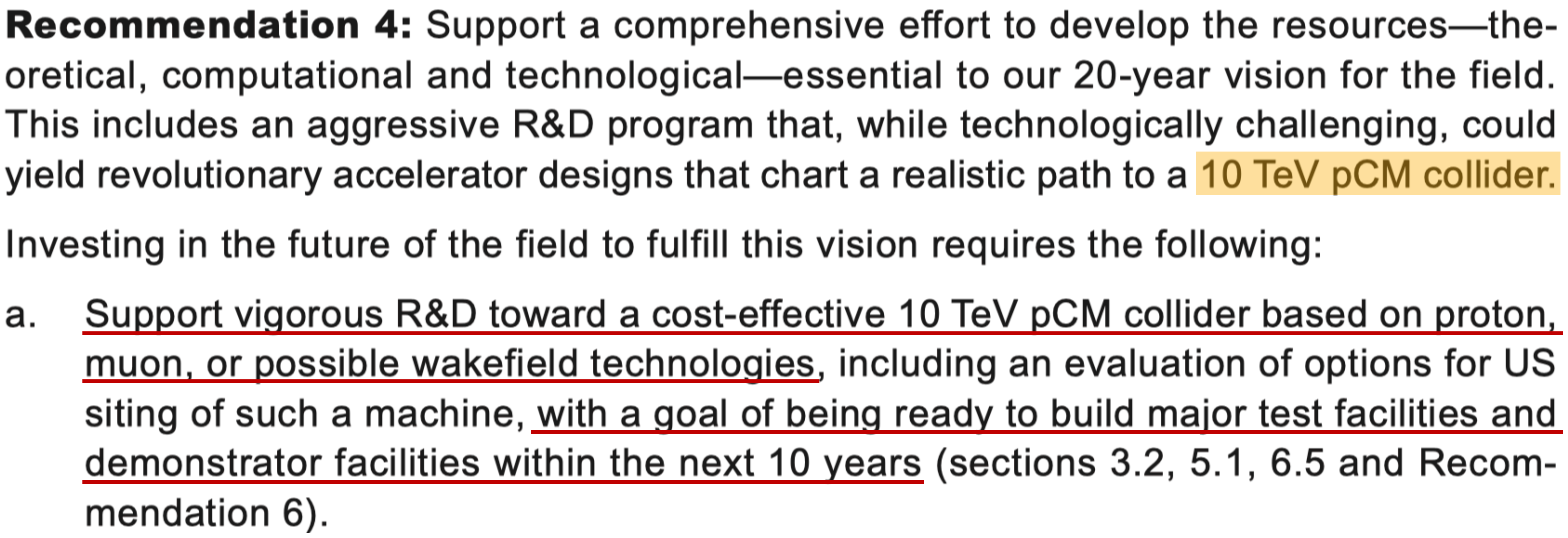

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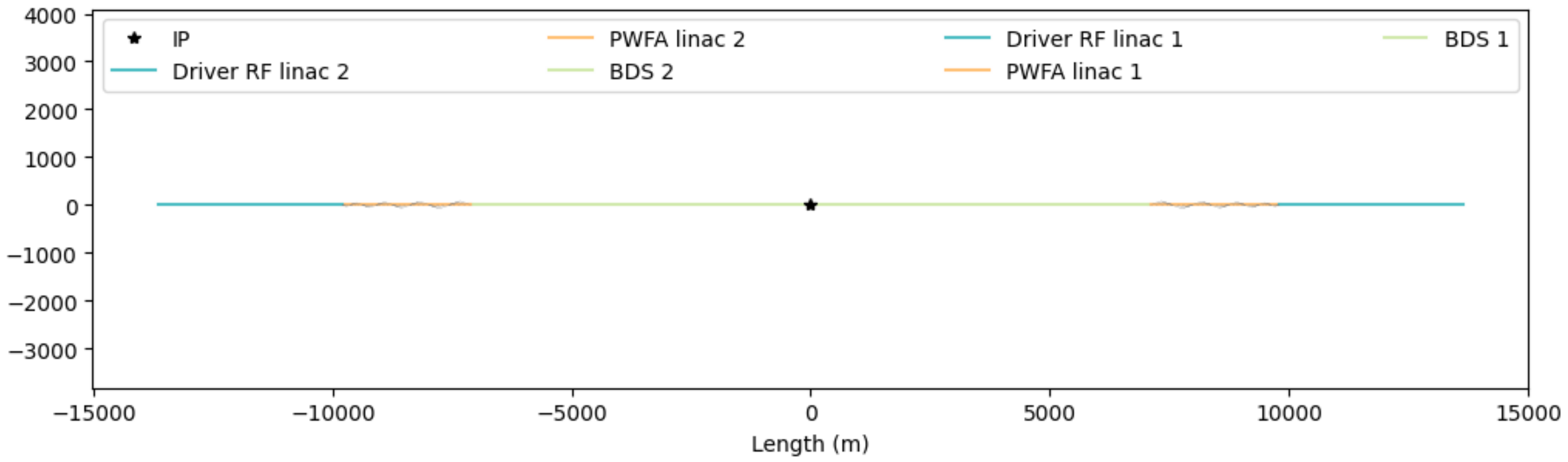
- Same tools developed for HALHF can be used for a 10 TeV-scale γ–γ collider using two e⁻ beams and similar PWFA linacs
  - *Estimated length: ~27 km (BDS is~14 km)*
  - *Luminosity and cost is difficult to estimate due to unknowns in gamma conversion (should not be scaled from HALHF)*



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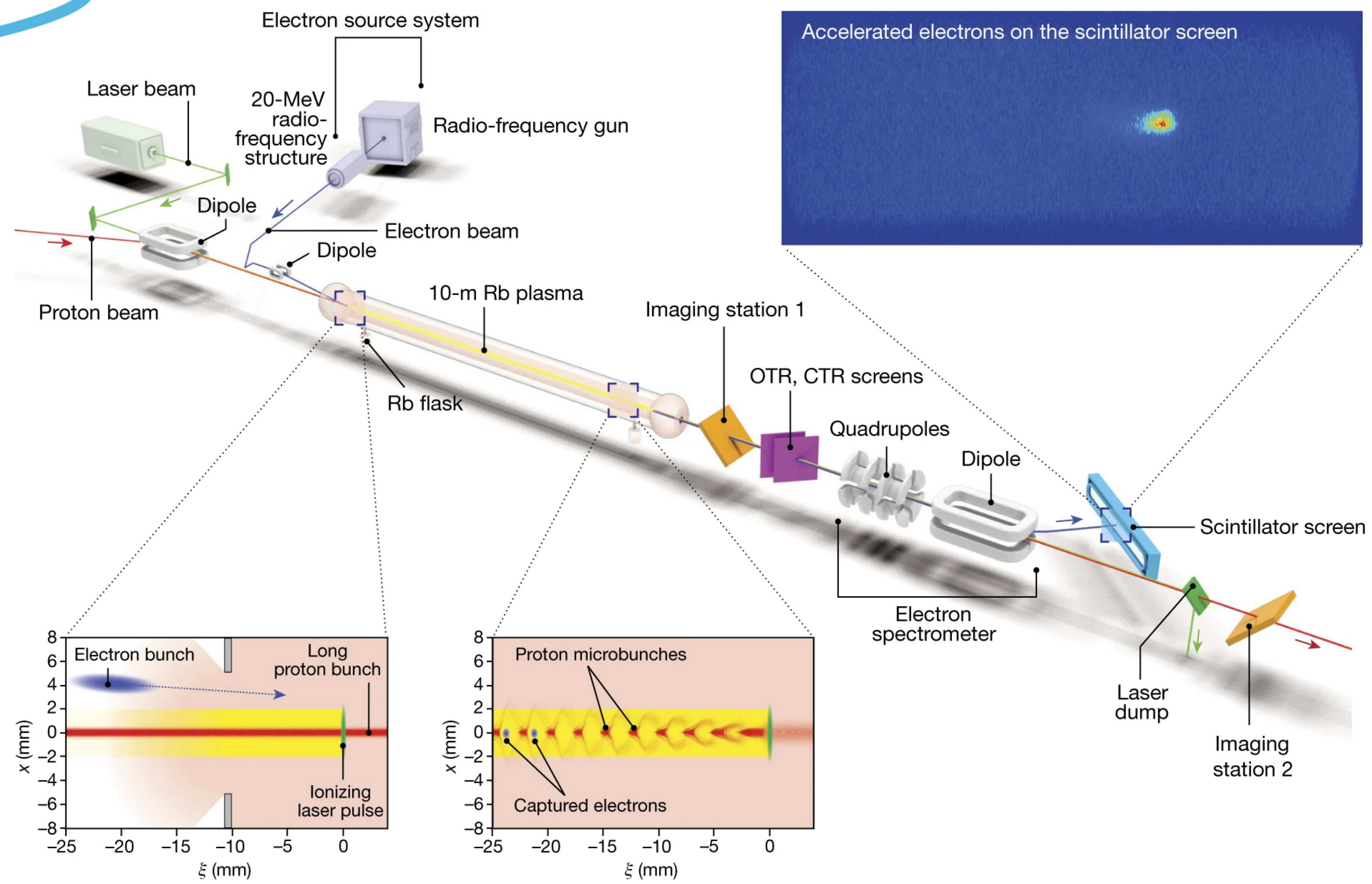
*but **RF** to **accelerate ~~positrons~~***

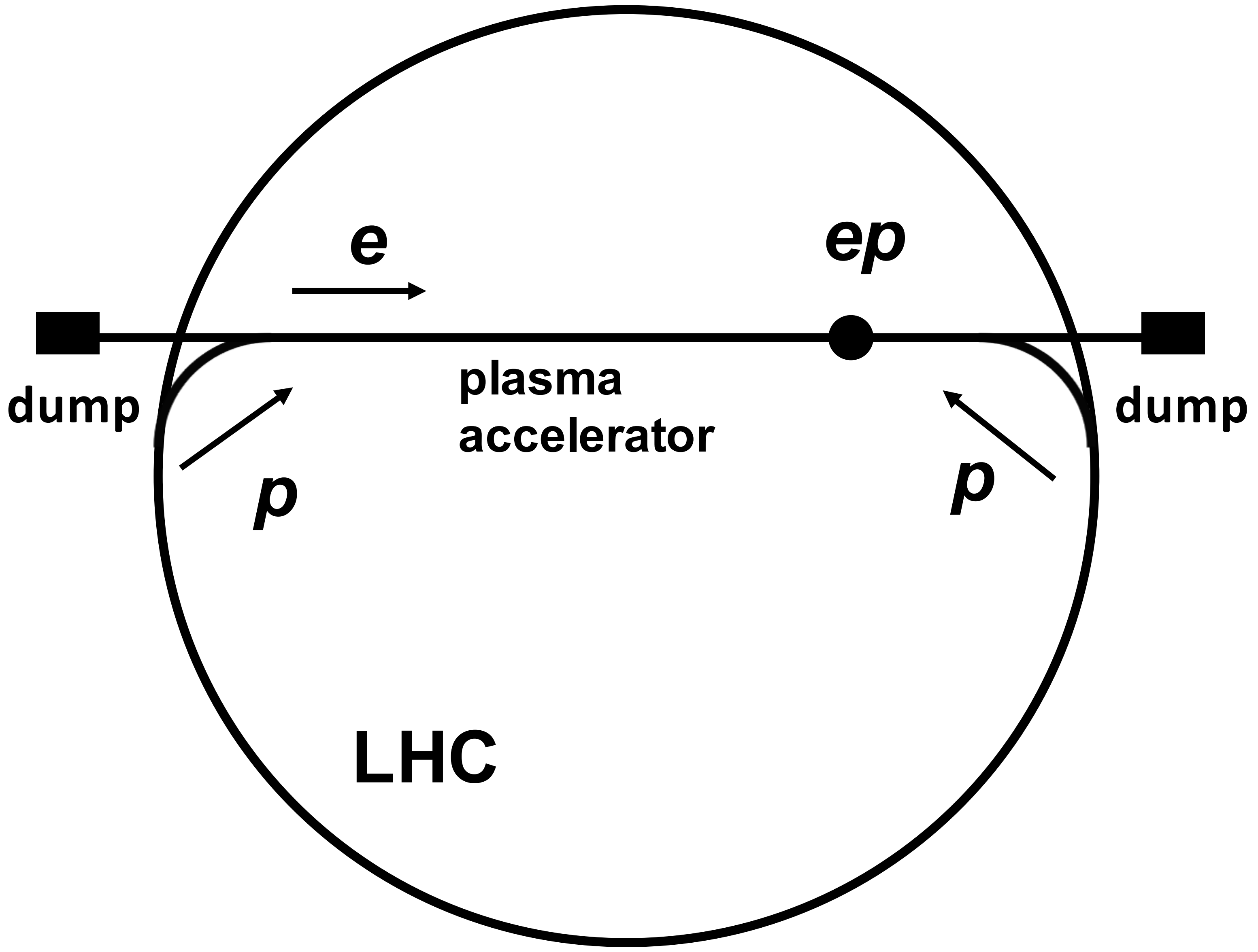
protons

Energy-frontier (multi-TeV CM) electron-proton collider

Leveraging excellent progress in proton-driven plasma accelerators at AWAKE



From: Adli et al. (AWAKE Collab.), Nature 561, 363 (2018)



From: A. Caldwell & M. Wing, Eur. Phys. J. C 76, 463 (2016)

- Acceleration to 2 GeV is a great achievement
- Experiment not optimised for electron injection
- ***Next goal***: acceleration to high energy with high quality

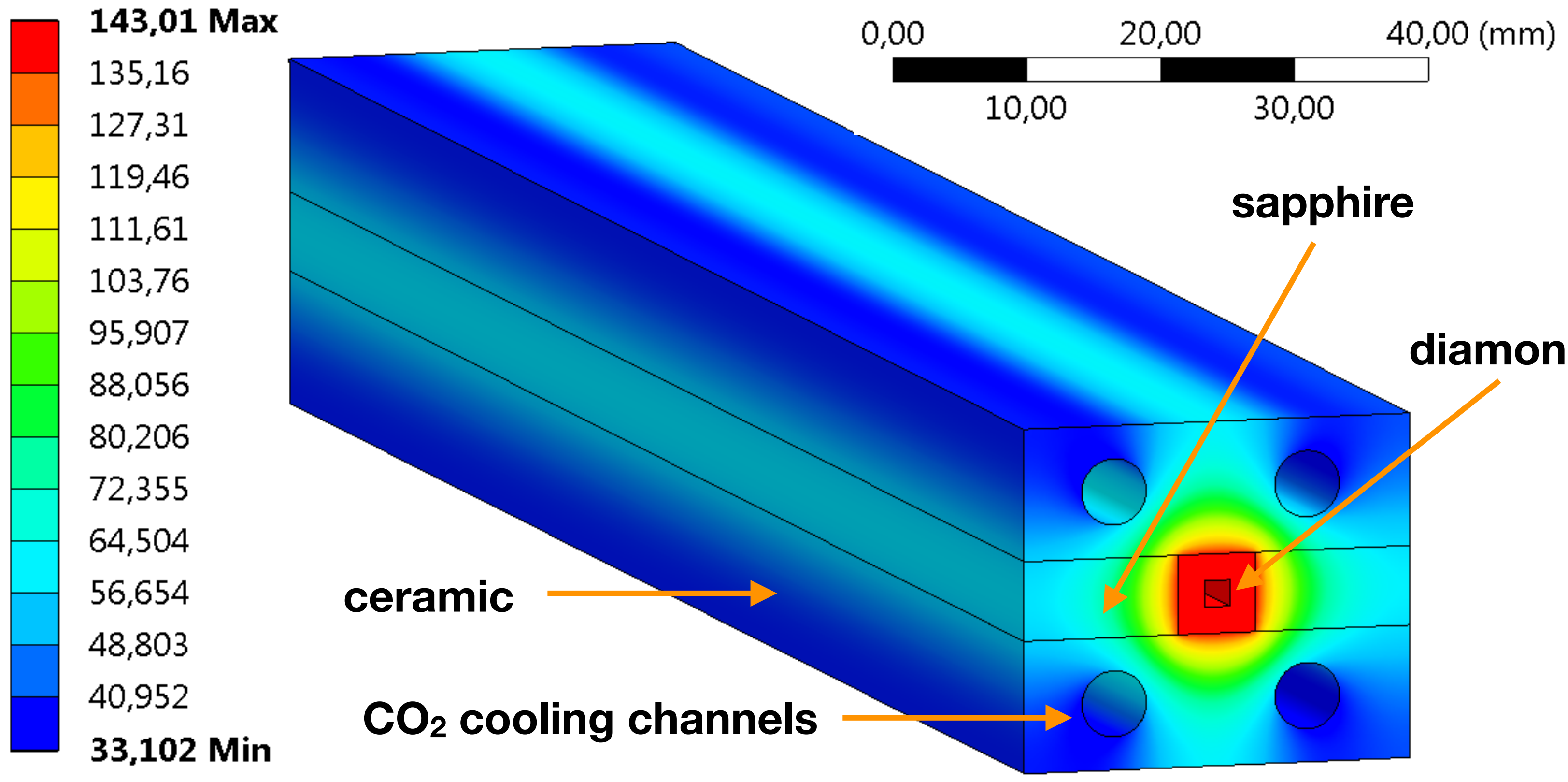
- ***First application***: fixed-target experiments for dark photon searches
- ***Ultimate application***: very high-energy (9 TeV CM) electron-proton collider
- ***Moon-shot application***: proton-driven plasma-based Higgs Factory (Farmer *et al.*, arXiv:2401.14765)

Outlook and plans

Many innovations and developments still required

Decouple the challenge to leverage existing facilities whilst planning for new ones

- *Experimental R&D in existing facilities:*
  - Single-stage operation with large energy gain and beam-quality preservation, with high overall efficiency
  - High repetition rate (optimised bunch-train pattern)
  - **High average power (plasma heating, cell cooling)**
  - Achromatic transport between stages



Concept for cooled plasma cells.
Image credit: R. D'Arcy

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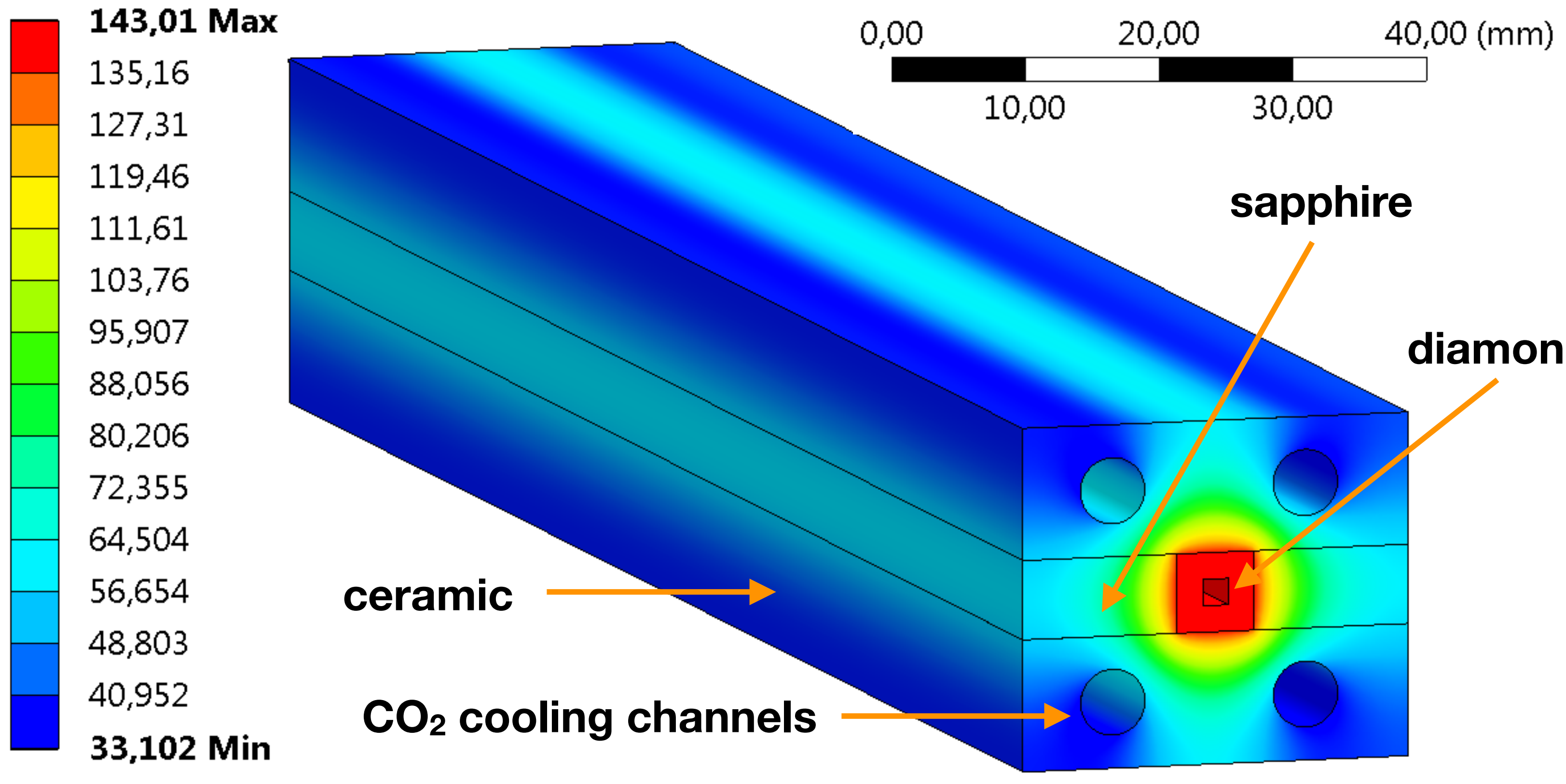
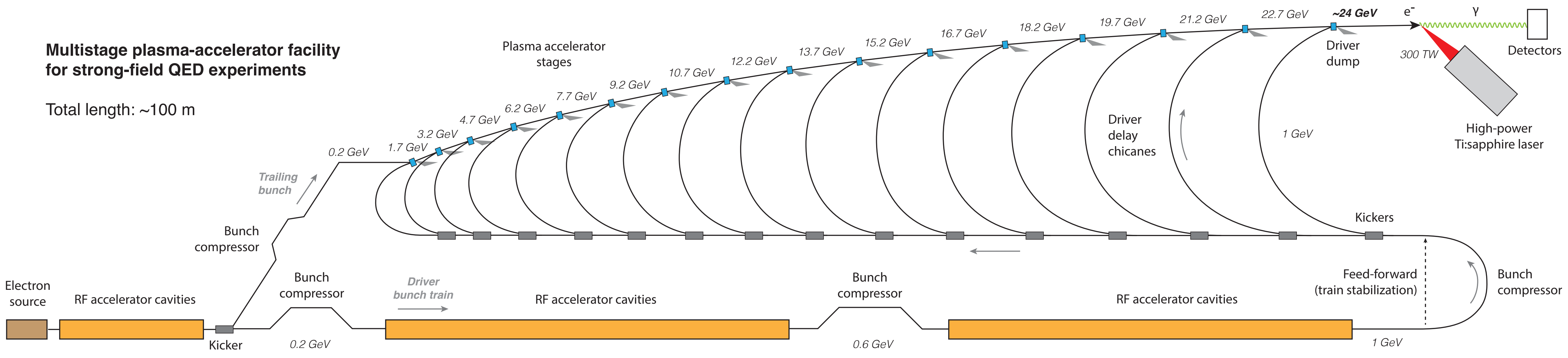
  - **Multi-stage demonstrator facility**
    - *O($10-100M) depending on final energy*
    - *Conceptual design in progress*
  - Spin polarisation



Concept for cooled plasma cells.
Image credit: R. D'Arcy



Concept for multi-stage demonstrator facility with strong-field QED experiment.
Image credit: C. A. Lindstrøm

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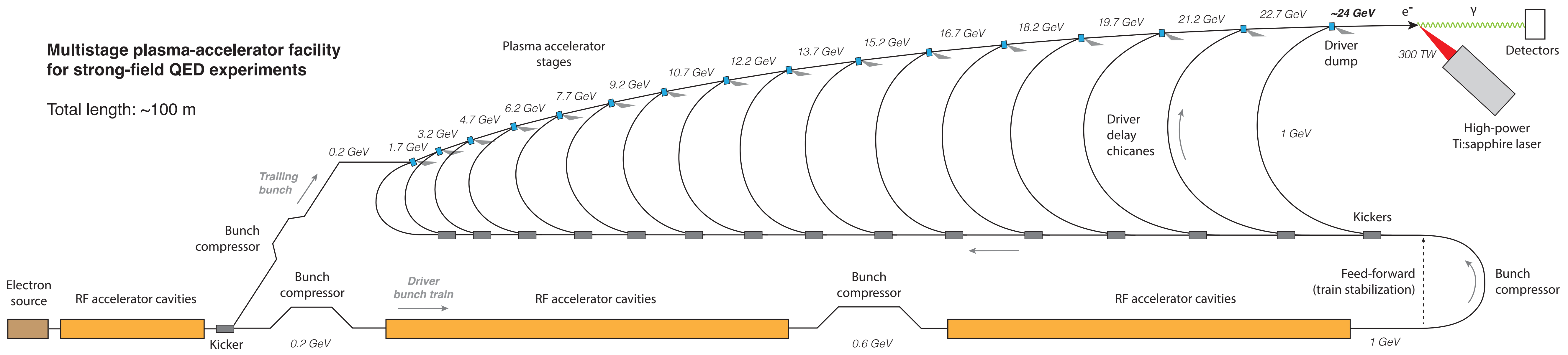
Possible intermediate infrastructures for HEP use:

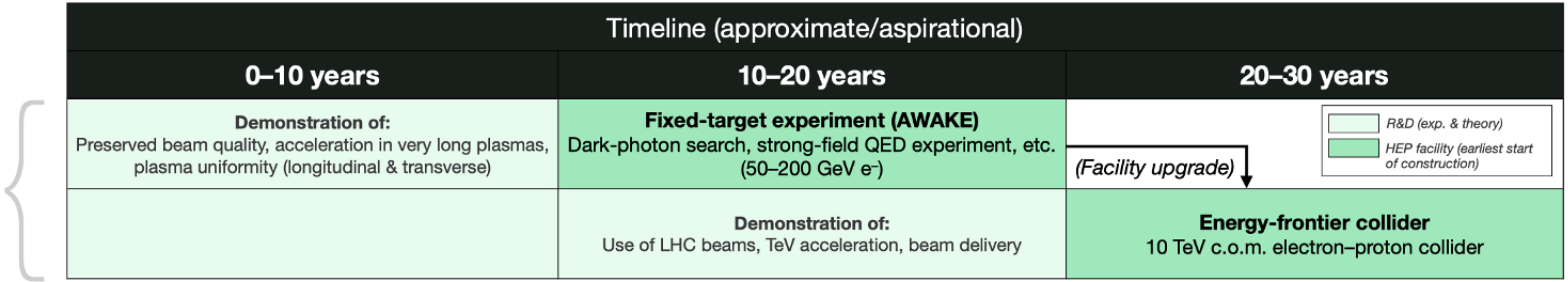
- Strong-field QED experimentation
- Plasma-based electron linac for LHeC
- Fixed-target experiment for dark-matter search
- Test-beam facility for detector development



Concept for multi-stage demonstrator facility with strong-field QED experiment.
Image credit: C. A. Lindstrøm

A staged approach to plasma-based collider readiness

The LDG Plasma-Accelerator R&D Roadmap for the ESPP Update

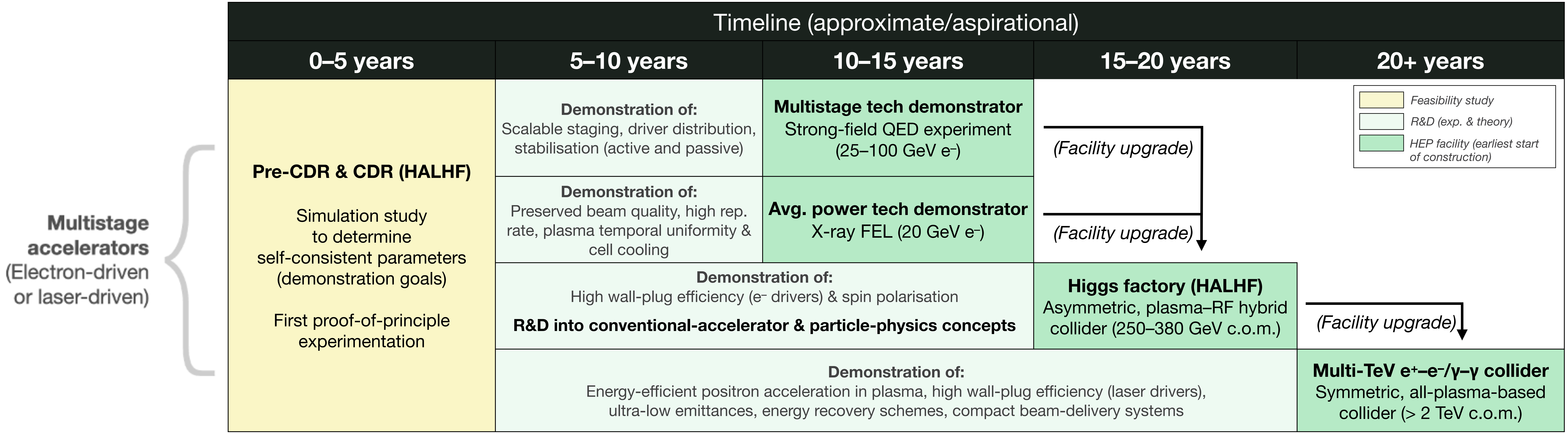


Timeline (approximate/aspirational)

	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)*
		Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy-frontier collider** 10 TeV c.o.m. electron–proton collider

R&D (exp. & theory)

HEP facility (earliest start of construction)



Timeline (approximate/aspirational)

	0–5 years	5–10 years	10–15 years	15–20 years	20+ years
Multistage accelerators (Electron-driven or laser-driven)	**Pre-CDR & CDR (HALHF)** Simulation study to determine self-consistent parameters (demonstration goals) First proof-of-principle experimentation	**Demonstration of:** Scalable staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25–100 GeV e^-)	*(Facility upgrade)*	
		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.)	*(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.)

Feasibility study

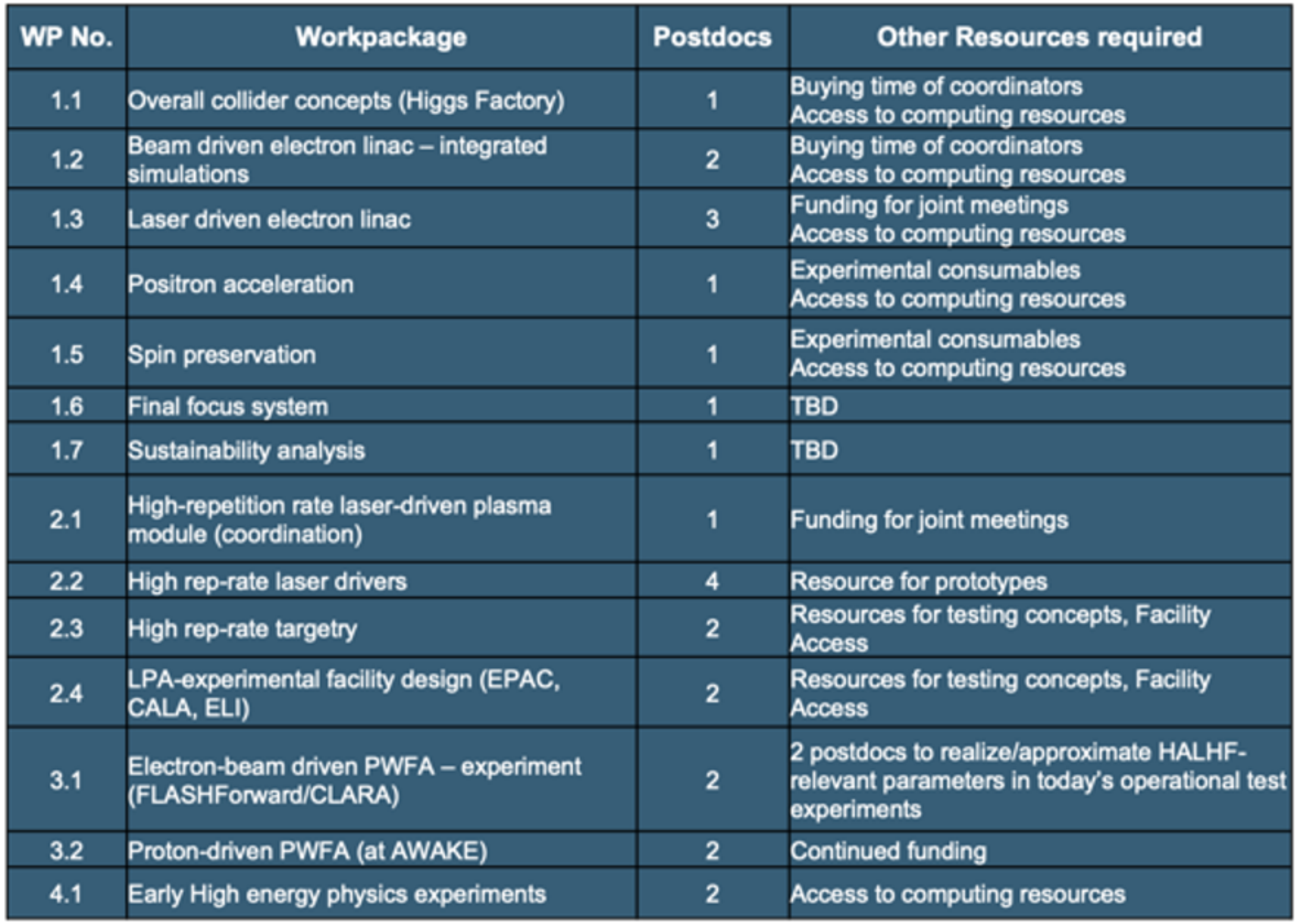
R&D (exp. & theory)

HEP facility (earliest start of construction)

Additional funding is required to achieve all proposed R&D

The LDG Plasma-Accelerator R&D Roadmap for the ESPP Update

ESPP Roadmap for Plasma Accelerators —
Working Packages and Required Resources



WP No.	Workpackage	Postdocs	Other Resources required
1.1	Overall collider concepts (Higgs Factory)	1	Buying time of coordinators Access to computing resources
1.2	Beam driven electron linac – integrated simulations	2	Buying time of coordinators Access to computing resources
1.3	Laser driven electron linac	3	Funding for joint meetings Access to computing resources
1.4	Positron acceleration	1	Experimental consumables Access to computing resources
1.5	Spin preservation	1	Experimental consumables Access to computing resources
1.6	Final focus system	1	TBD
1.7	Sustainability analysis	1	TBD
2.1	High-repetition rate laser-driven plasma module (coordination)	1	Funding for joint meetings
2.2	High rep-rate laser drivers	4	Resource for prototypes
2.3	High rep-rate targetry	2	Resources for testing concepts, Facility Access
2.4	LPA-experimental facility design (EPAC, CALA, ELI)	2	Resources for testing concepts, Facility Access
3.1	Electron-beam driven PWFA – experiment (FLASHForward/CLARA)	2	2 postdocs to realize/approximate HALHF-relevant parameters in today's operational test experiments
3.2	Proton-driven PWFA (at AWAKE)	2	Continued funding
4.1	Early High energy physics experiments	2	Access to computing resources

- ***Opportunity*:**
  - A compelling list of goals and activities
  - New activities are often leveraged by significant in-house activities at major labs
- ***Key challenge*:**
  - Progress is being made with percent-level input from existing academics and researchers e.g. pre-CDR document and ESPP update document for HALHF
  - But we need to acquire an **extra ~3M€/yr for ~5 yrs** for all the necessary R&D for HALHF and AWAKE
  - Funding required for people, hardware, HPC, etc.

Conclusions

- Plasma accelerator technology is of high interest for the future of particle physics
  - Reduce the size of future colliders (reduced construction cost, environmental impact)
  - Upgrade path for Higgs-Factory linear colliders (repurposing of ILC/CLIC/C^3 infrastructure)
- The community is making progress to deliver self-consistent concepts
  - Higgs Factory → HALHF collaboration is pioneering system integration and optimisation (***ESPP***)
  - Energy Frontier → 10 TeV pCM wakefield collider end-to-end design effort launched in US (***P5***)
- What is needed for these studies to be successful?
  - Continued international AAC community engagement
  - Close partnership with particle physics theorists & experimentalists (physics case, detectors)
  - Targeted funding (primarily personnel)
- An opportunity for UK leadership
  - World-leading expertise in novel-accelerator research
  - State-of-the-art novel-accelerator facilities (e.g. EPAC, CLARA) at open-minded labs (e.g. RAL, Daresbury)