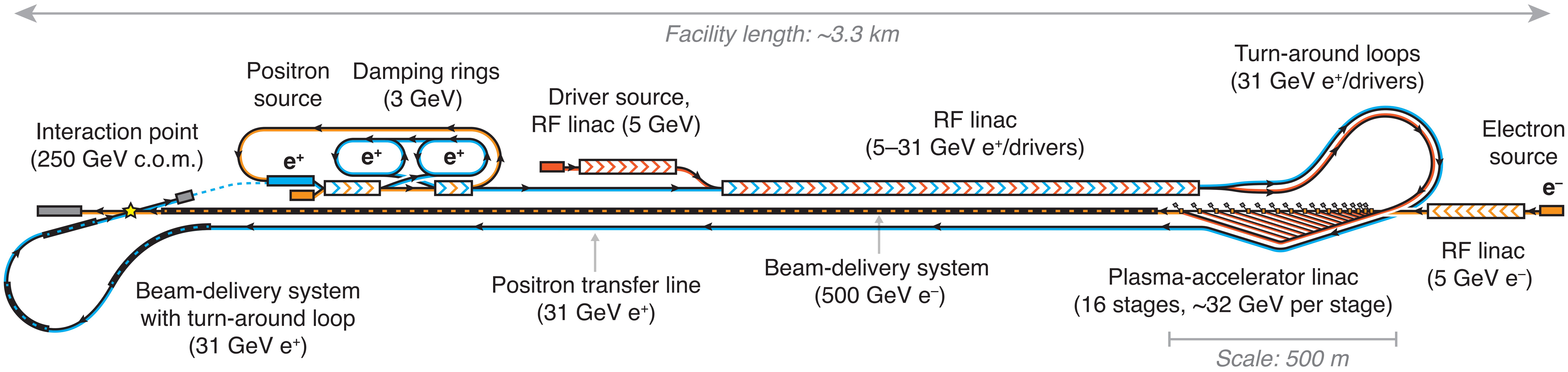

A Hybrid, Asymmetric, Linear Higgs Factory (HALHF)

Updates and Upgrades

Richard D'Arcy

University of Oxford

Brian Foster, Carl A. Lindstrøm

University of Oxford/DESY & University of Oslo

20 Mar 2024 | ALEGRO Workshop | Lisbon

Outline

- > Motivation and concept
- > Recent progress
- > Upgrade paths
- > Conclusions

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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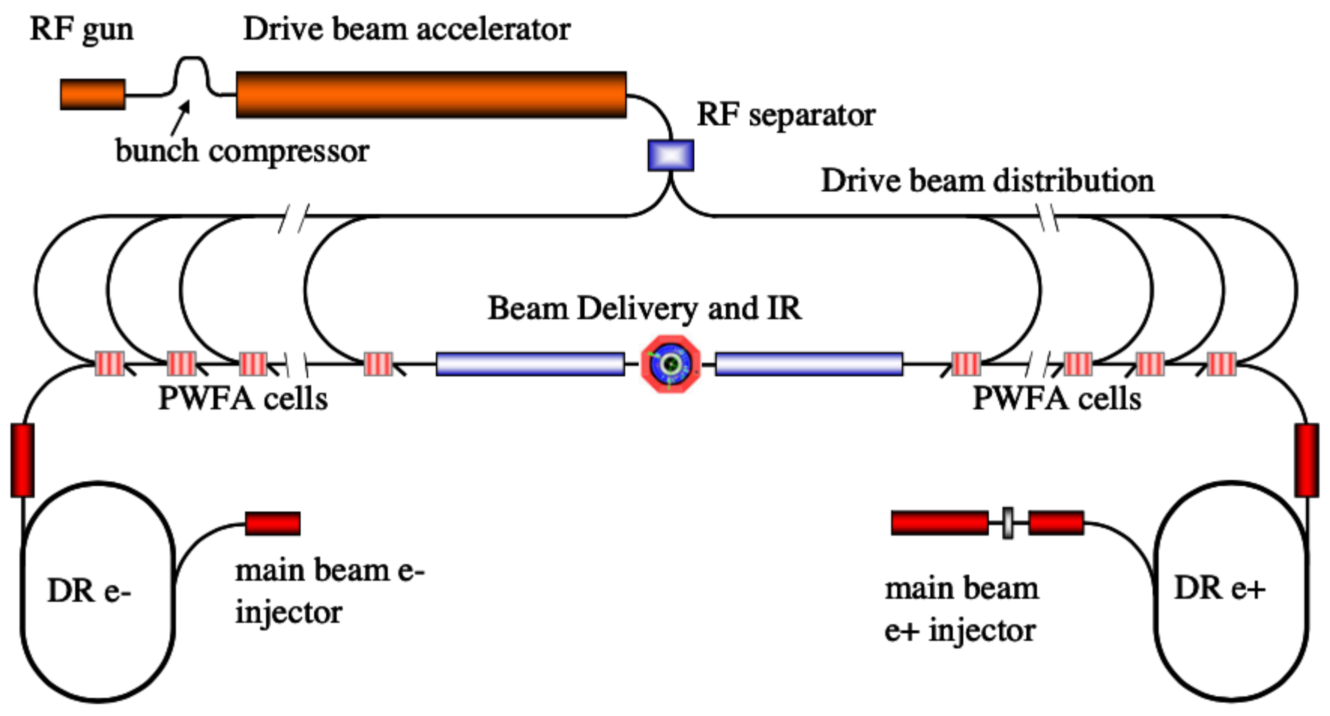
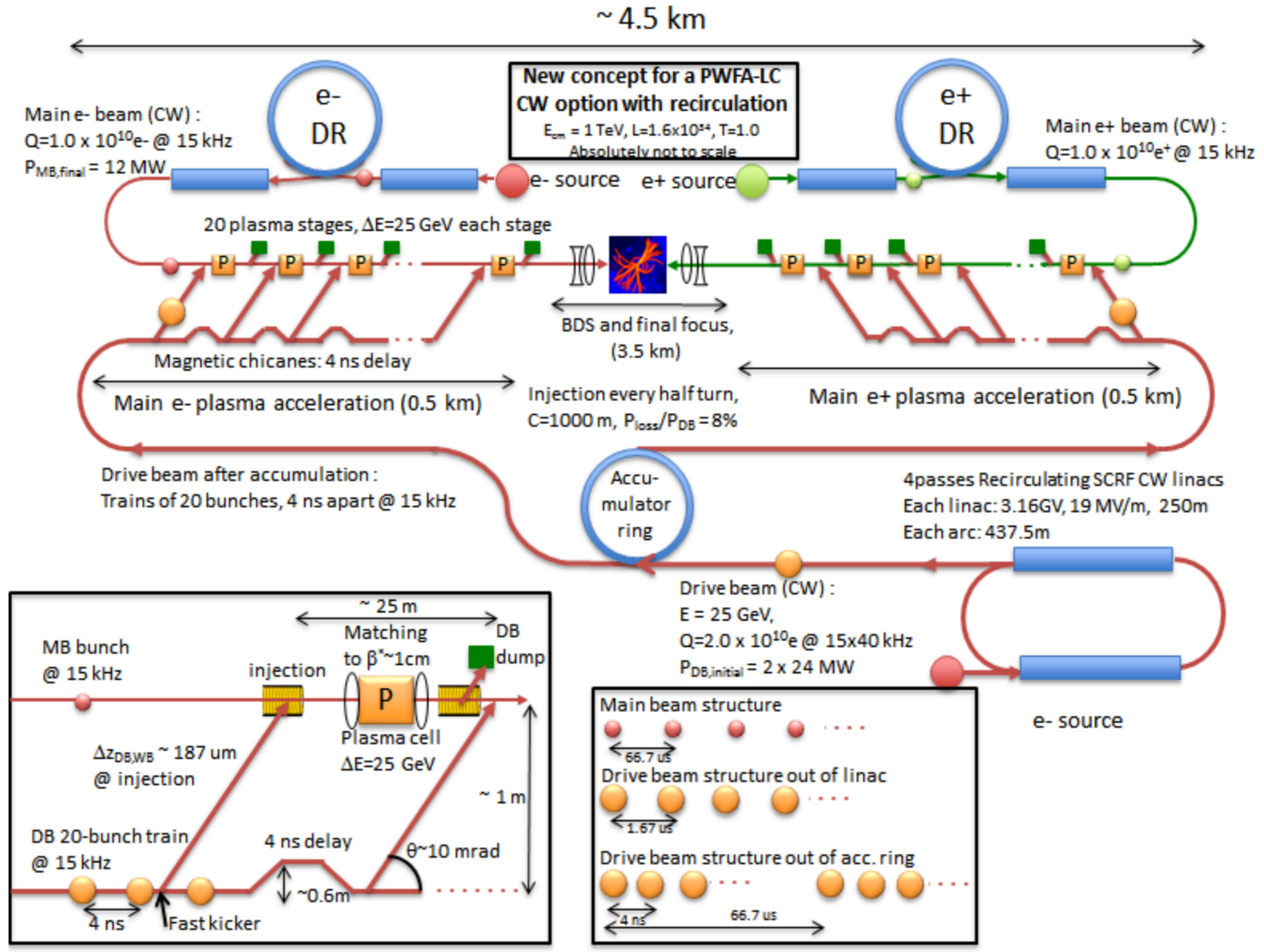
  - *Adli et al. (2013)*
- **Very useful exercises to focus R&D at the time**



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



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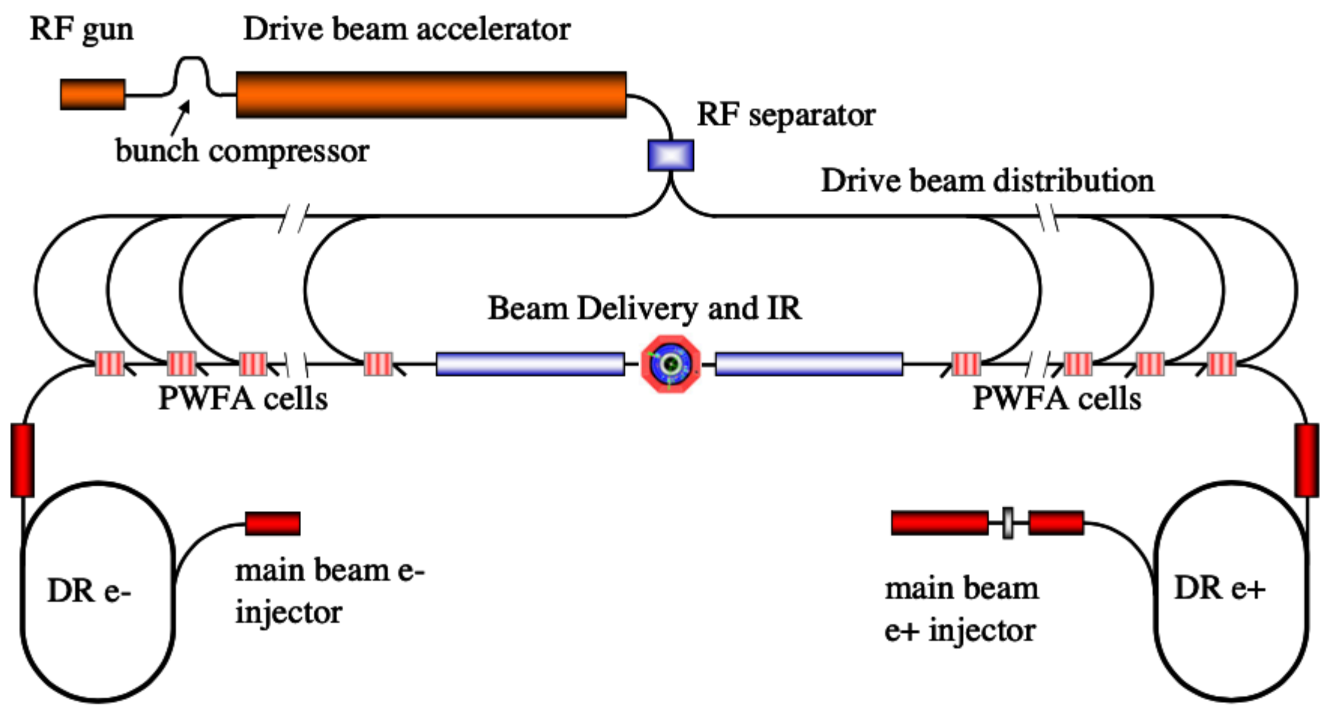
- Still one key stumbling block… ***positrons!***
- Plasmas = charge asymmetric ➞ no 'blowout' for e^+



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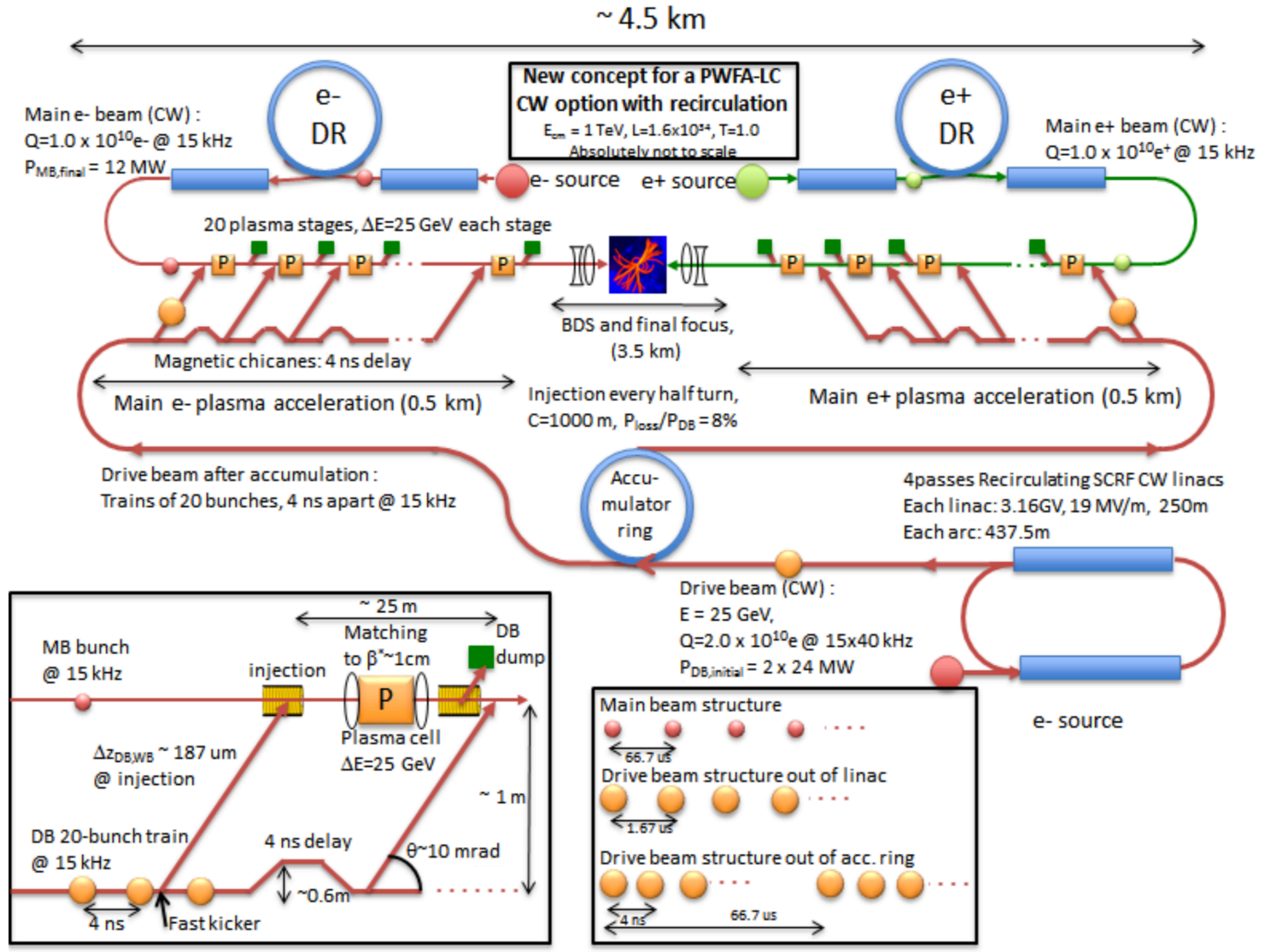


Source: Adli et al., Proc. Snowmass (2013)

The pragmatic approach:

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

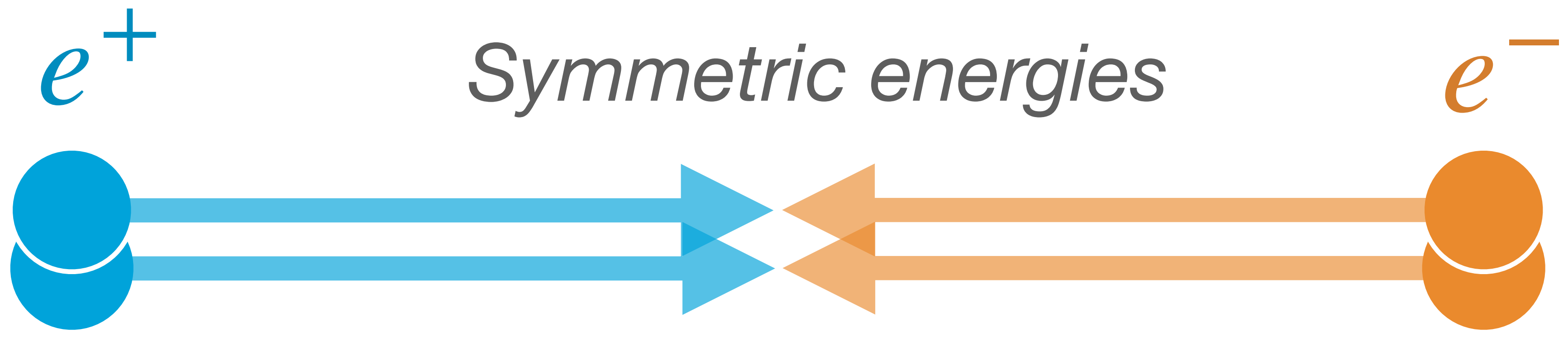
but **RF** to **accelerate positrons**

Can we use **asymmetric e^+/e^- energies**? Yes!

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

- Electron (E_e) and positron energies (E_p) must follow: $E_e E_P = s/4$ $E_e + E_P = \gamma\sqrt{s}$
  - 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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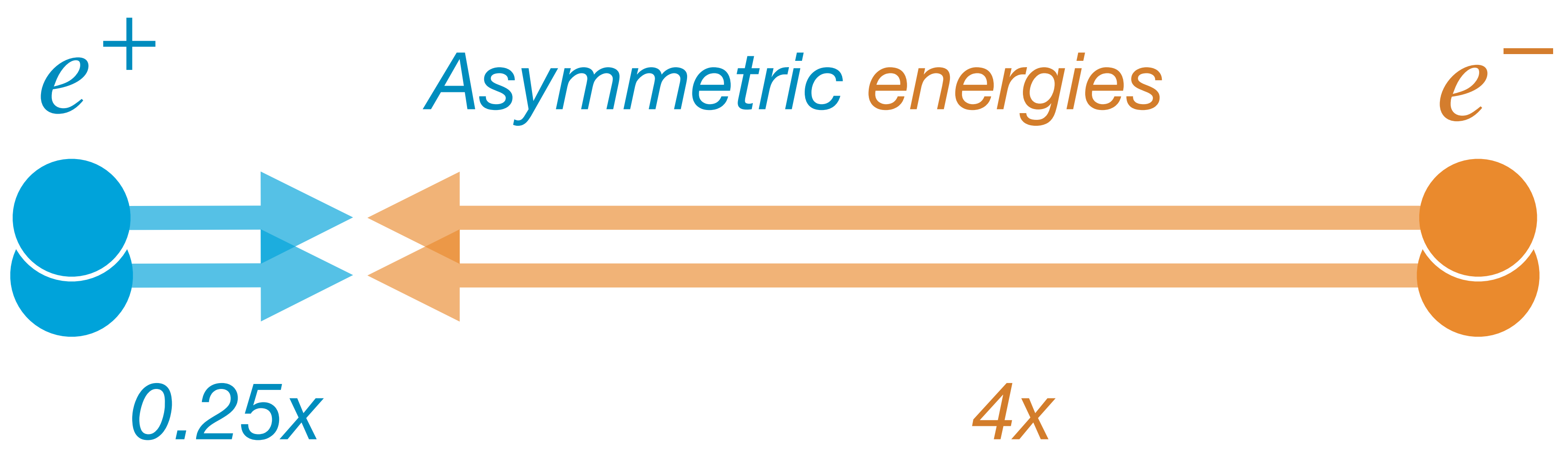
$$\gamma = \frac{1}{2}\left(\frac{2E_p}{\sqrt{s}} + \frac{\sqrt{s}}{2E_p}\right)$$

- A reasonable (but not necessarily optimised) 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:

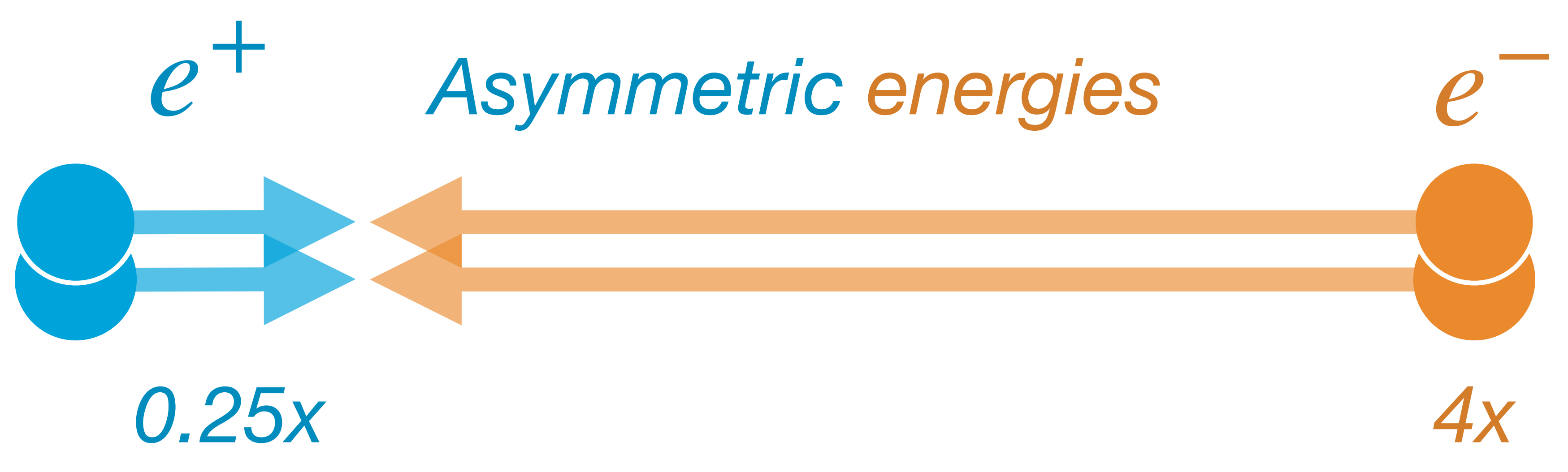
ILC params (→ first row)

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)



Asymmetries everywhere → charge

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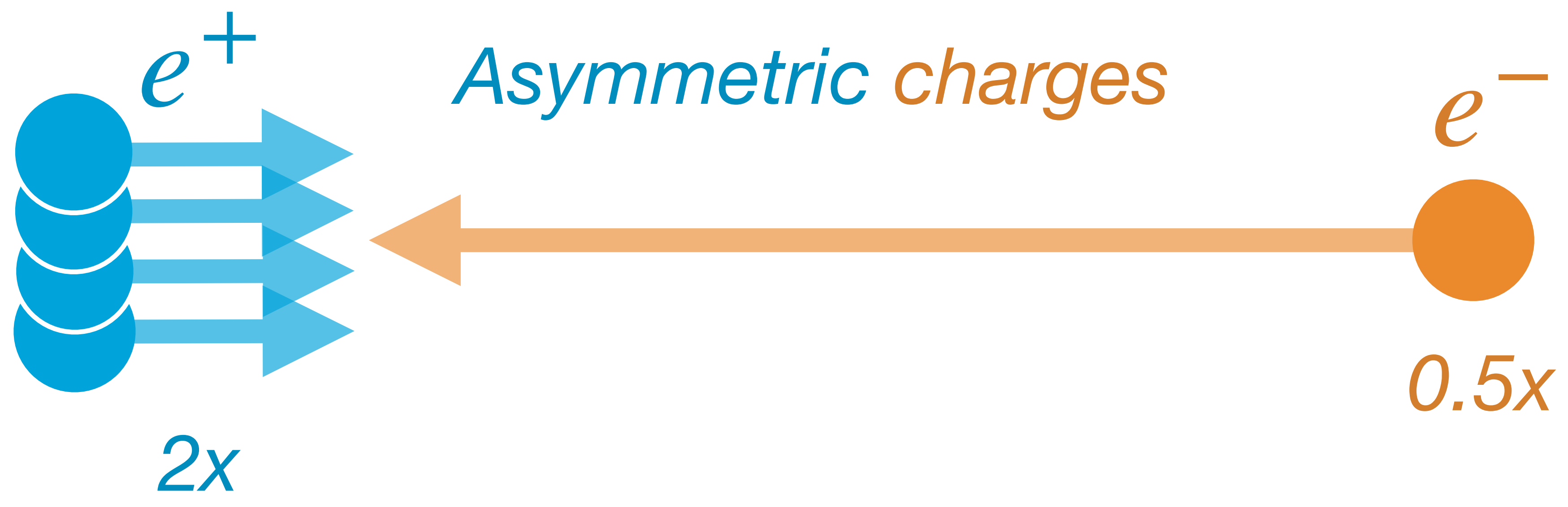
31.3 / 500	75 / 75	4 / 1	10 / 10	35 / 35	3.3 / 52	0.10 / 1.6	1.04	0.60	1.25

> Power consumption increase: $$\frac{P}{P_0} = \frac{N_{e^-}E_{e^-} + N_{e^+}E_{e^+}}{N\sqrt{s}}$$

> **Unchanged power usage if $N_e/N_p = E_p/E_e$** (here: 4x more e^+, 4x less e^-)



Asymmetries everywhere → emittance

> GUINEA-PIG beam–beam simulations:

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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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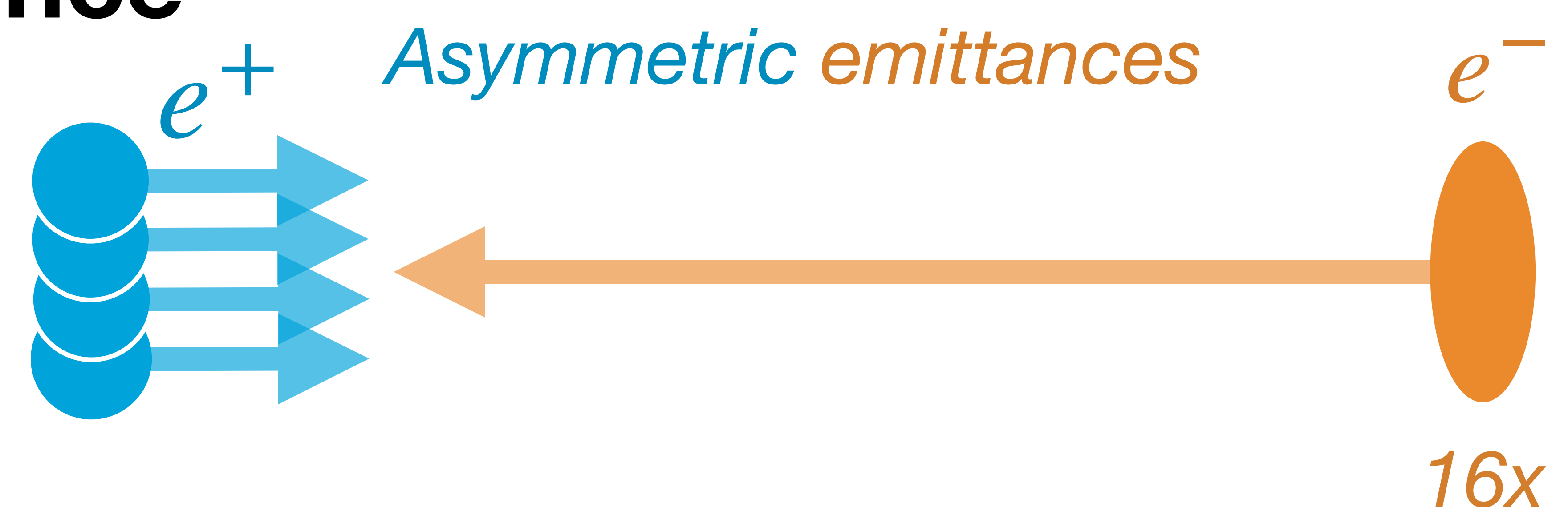
31.3 / 500	75 / 75	4 / 1	10 / 40	35 / 140	3.3 / 13	0.10 / 0.41	1.01	0.58	1.25
31.3 / 500	75 / 75	4 / 1	10 / 80	35 / 280	3.3 / 6.5	0.10 / 0.20	0.94	0.54	1.25
31.3 / 500	75 / 75	4 / 1	10 / 160	35 / 560	3.3 / 3.3	0.10 / 0.10	0.81	0.46	1.25

> *Geometric* emittance scales as (energy)$^{-1}$

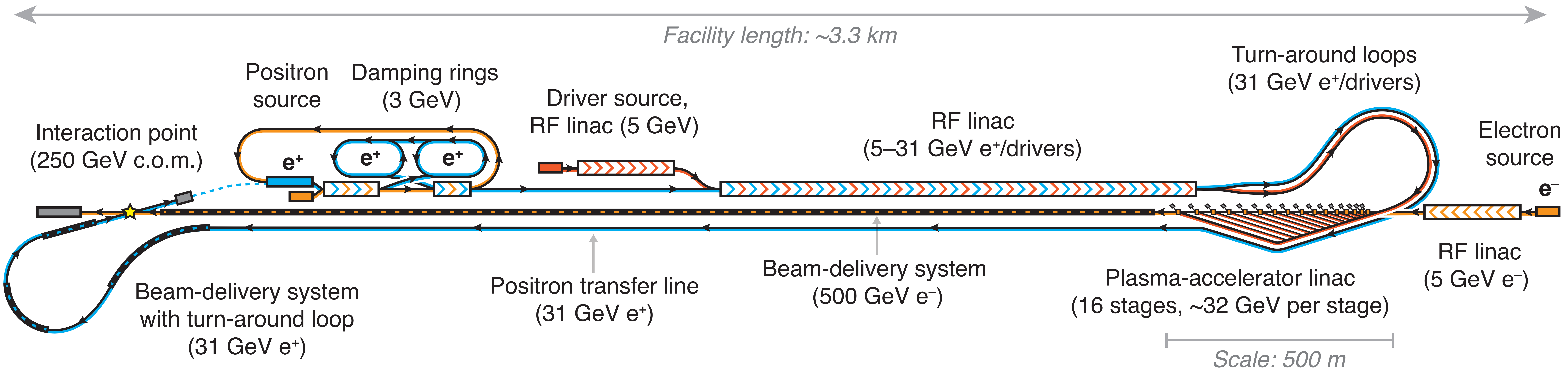
> e^+ **must have smaller IP beta function (lower energy)**: 3.3/0.1 mm (CLIC-like → *possible*)

> **Apply similar principle for the e^- (*normalised*) emittance**

> Decrease IP beta function to allow emittance increase



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
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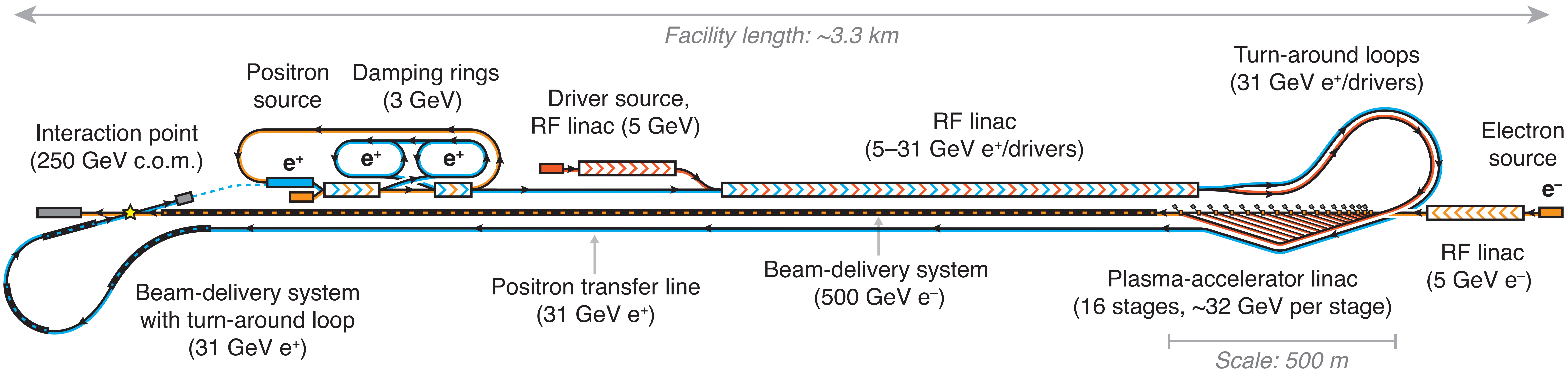

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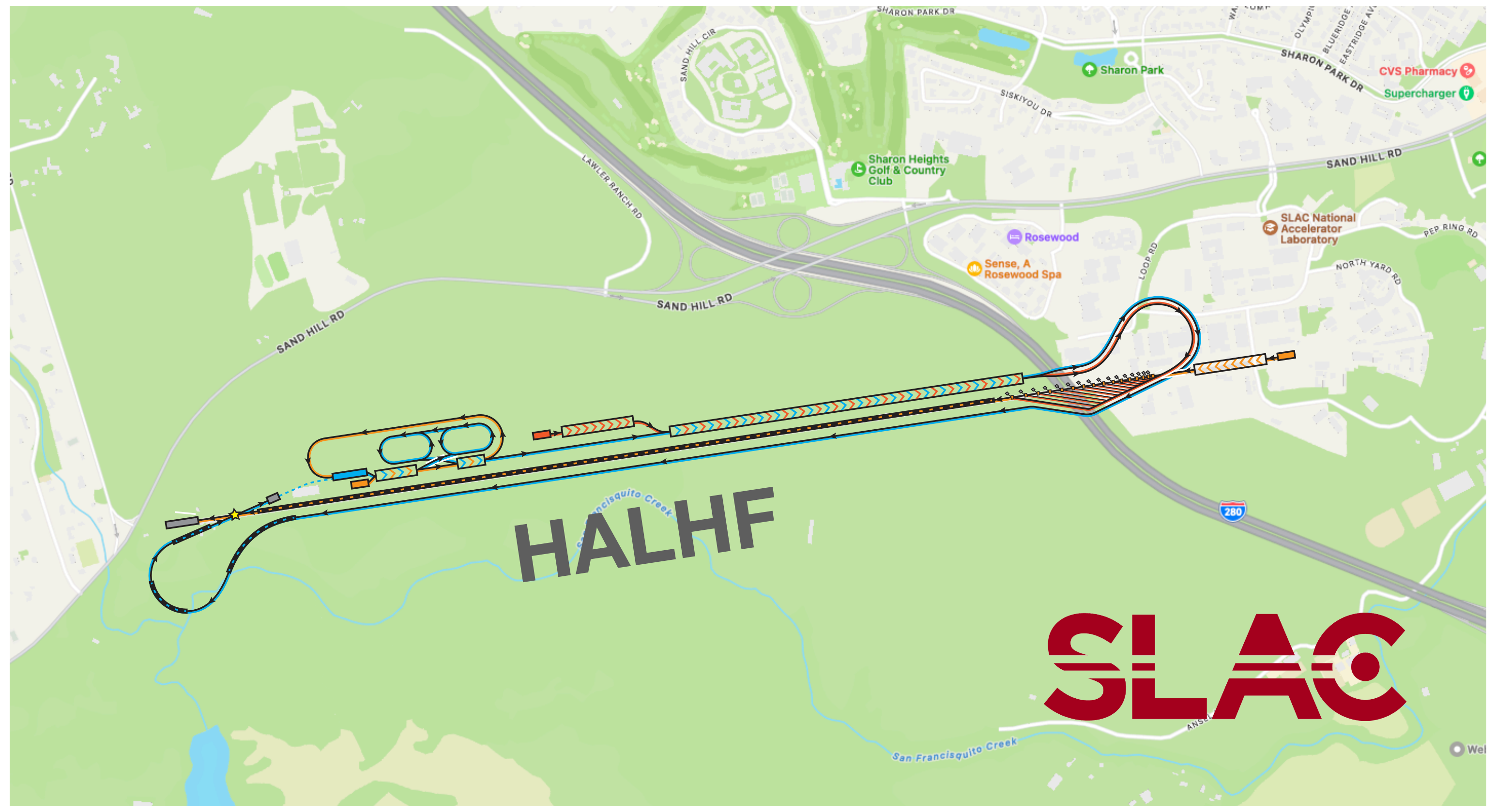

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Engagement with the community has given us a lot to think about

- A ‘realistic’ scheme provides a vehicle to push forward required R&D
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    - **Transverse instabilities** (*too large of an emittance growth*)
    - **Beam ionisation** (*the beam density and hence peak E-field is too high*)

Possible solution #1: Lower the plasma density (and beam density)

- ***Downside:* Lower density reduces the accelerating gradient**
  - It turns out the gradient is not so crucial (*a major lesson learnt from HALHF, though this will be less true at multi-TeV*)
  - At ~1 GV/m (*x6.4 lower*) the PWFA arm is ~850 m (*x2 longer ➞ interstage optics dominate*)
- ***Upside:* Everything else is easier**
  - The cell cooling requirements go down (*scales as E_z*) from ~90 to ~15 kW/m (*CLIC-like*)
  - Transverse instabilities are reduced (*parameter/jitter studies required to quantify exactly*)
  - Ionisation potential of the beam is reduced (*beam density goes down*), which permits use of heavier gases like xenon (*also desired for reduced ion motion*)
  - Matching, alignment, and synchronisation tolerances reduced (*beta functions are larger*)
  - Bunches are longer, currents are lower (*less compression/stretching required*)
- ***Synergy***: Longer plasma cells required — starting to look a lot like AWAKE!

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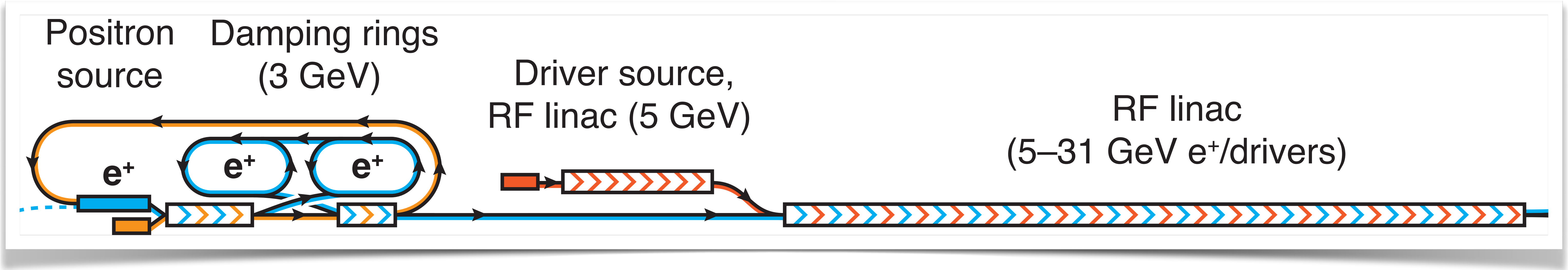

Possible solution #2: Decouple the dual-purpose (e^+ & e^--driver) linac

- ***Downside:*** **Two linacs required instead of one**
  - Footprint may increase (*more tunnel, larger CO_2 output in build*)
- ***Upside:*** **Everything else is easier (again)**
  - Low-power, high-gradient linac for e^+ (*shorter, cheaper*)
  - High-power, low-gradient linac for e^- drivers (*possibly cheaper in combination with e^+ linac*)
  - Reduced power per drive-beam dump (*lower energy drivers e.g. 31 ➞ 10 GeV*)
  - More flexibility over drive-beam current profiles (*higher transformer ratio*)
  - No turnaround loops (*straighter/longer tunnels but possibly less volume in total*)
- ***Synergy***: More compatible with laser-based upgrades — a like-for-like switch of driver linac for stacked high-power-laser systems

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  - **High-voltage and high-power linac** (*technically challenging*)
  - **Flat beams** (*emittance mixing from transverse coupling*)

Possible solution #3: Flat beam drivers?

- ***More info***:
  - S. Diederich's talk tomorrow morning
  - S. Diederichs *et al.*, "Resonant emittance mixing of flat beams in plasma accelerators", arXiv:2403.05871 (2024)

Outline

- > Motivation and concept
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- > Upgrade paths → *Lindstrøm, D'Arcy, Foster, arXiv:2312.04975 (2024)*
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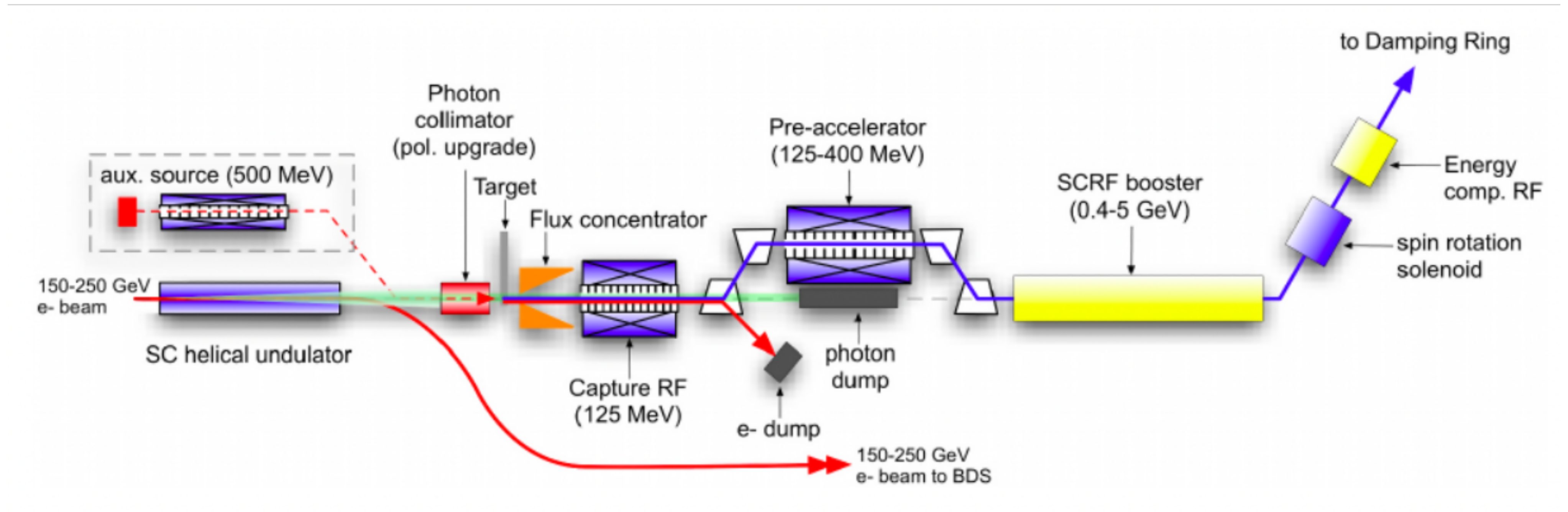
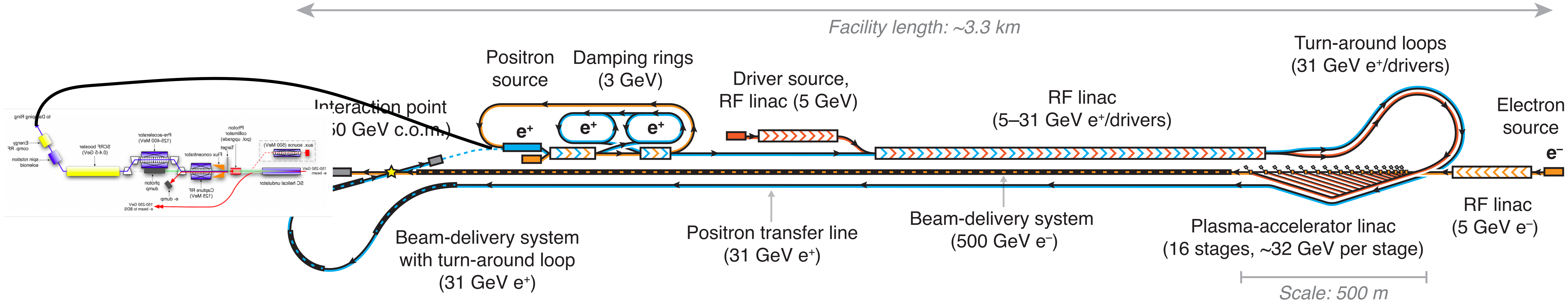
Upgrade: **Polarised positrons**

- 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 increase of 5–10% of original (+ ~100M€)

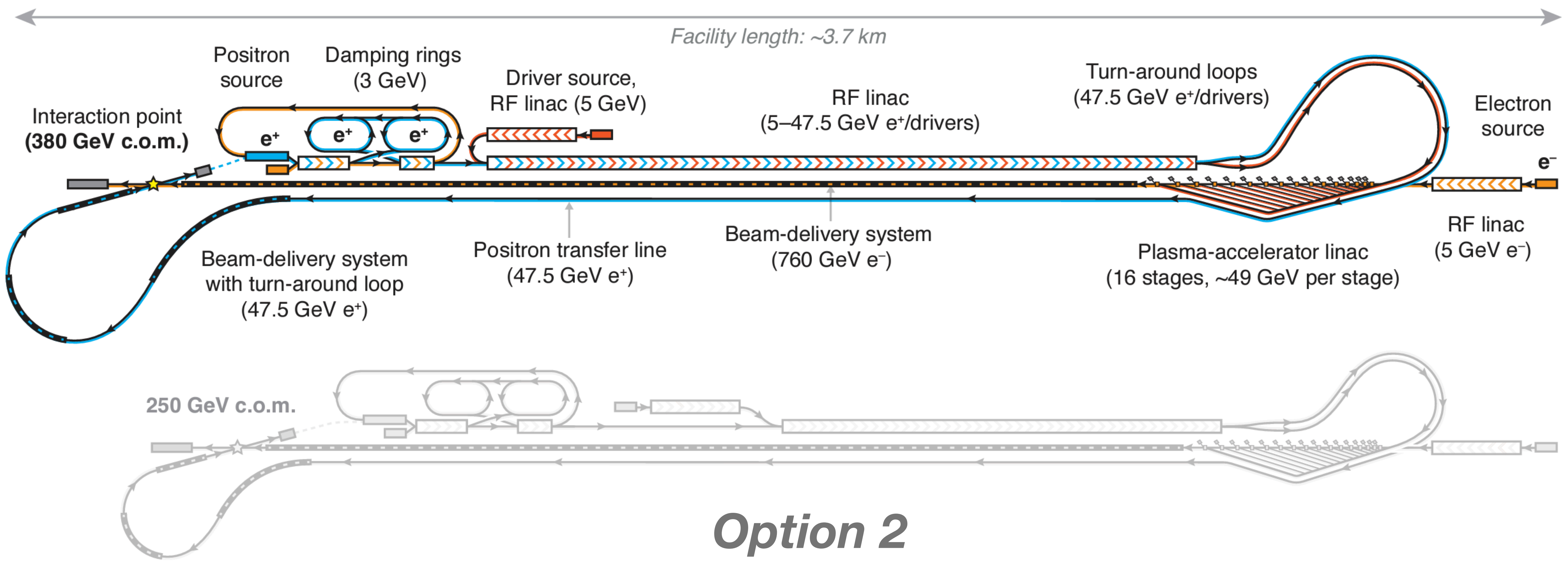




Source: [Lindstrøm, D'Arcy, Foster, arXiv:2312.04975 (2024)]

Upgrade: **380 GeV centre of mass**

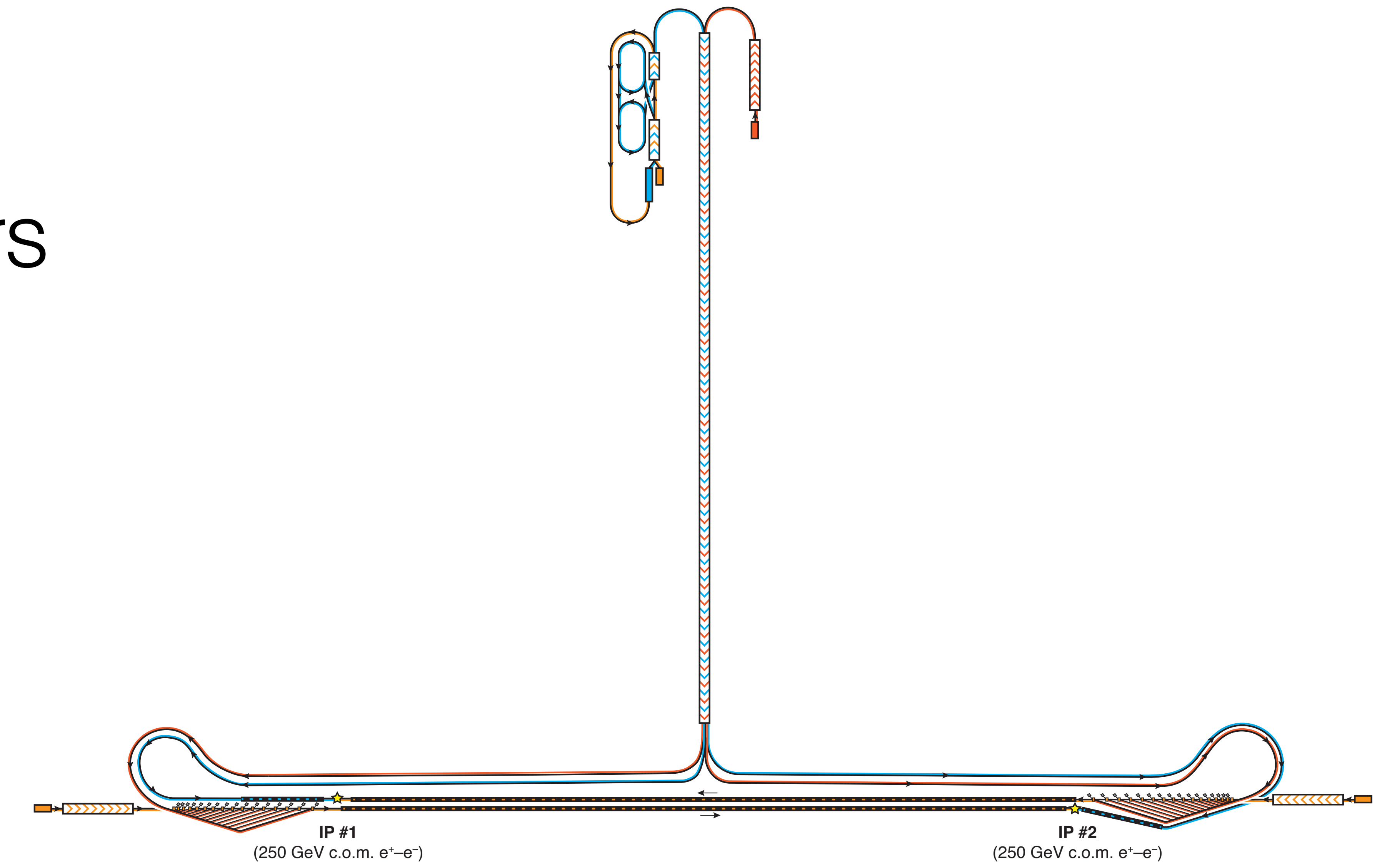
- Operation at the t–tbar threshold (346 GeV) typically motivates a c.o.m. up to 380 GeV
  - … which is in fact the minimum energy proposed for CLIC
- Two options:
  - 31 GeV positrons / **1165 GeV electrons** (more plasma stages, higher γ, lower efficiency) ➞ +1 km PWFA linac
  - **47.5 GeV positrons** / **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

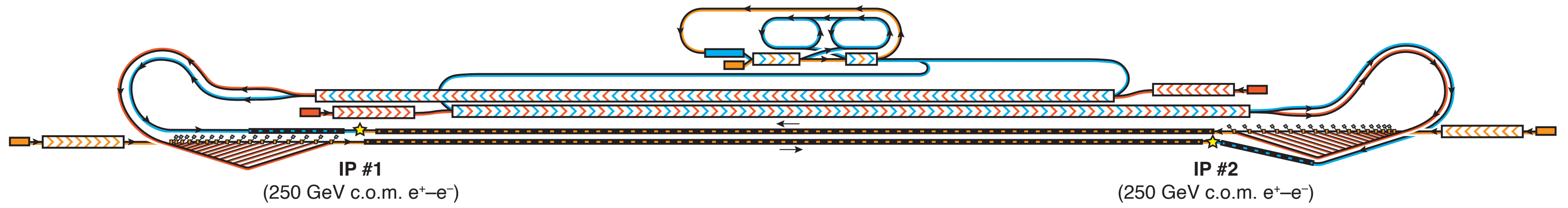


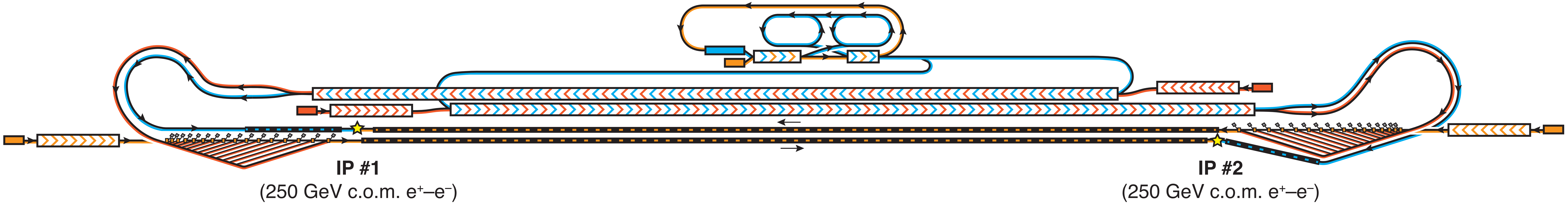
Option 2

Upgrade: **Two interaction points**

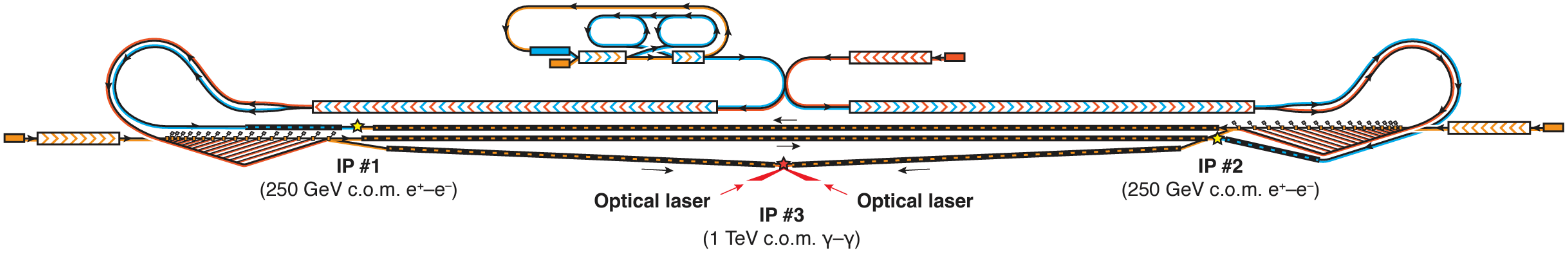
> Single IP traditionally seen as problematic for linear colliders
> Opportunity for HALHF:
  > Overlap/reuse the high-energy-electron BDS tunnel
  > Overall footprint increases only marginally
> Requires either a transverse linac for shared power (+15% cost) or two RF linacs for 2x power (+35% cost)
> May be important politically (systematics, 2x physicists)





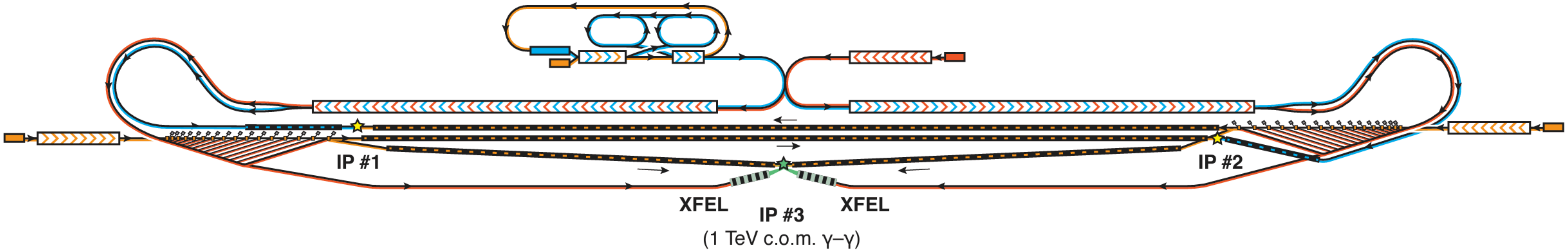


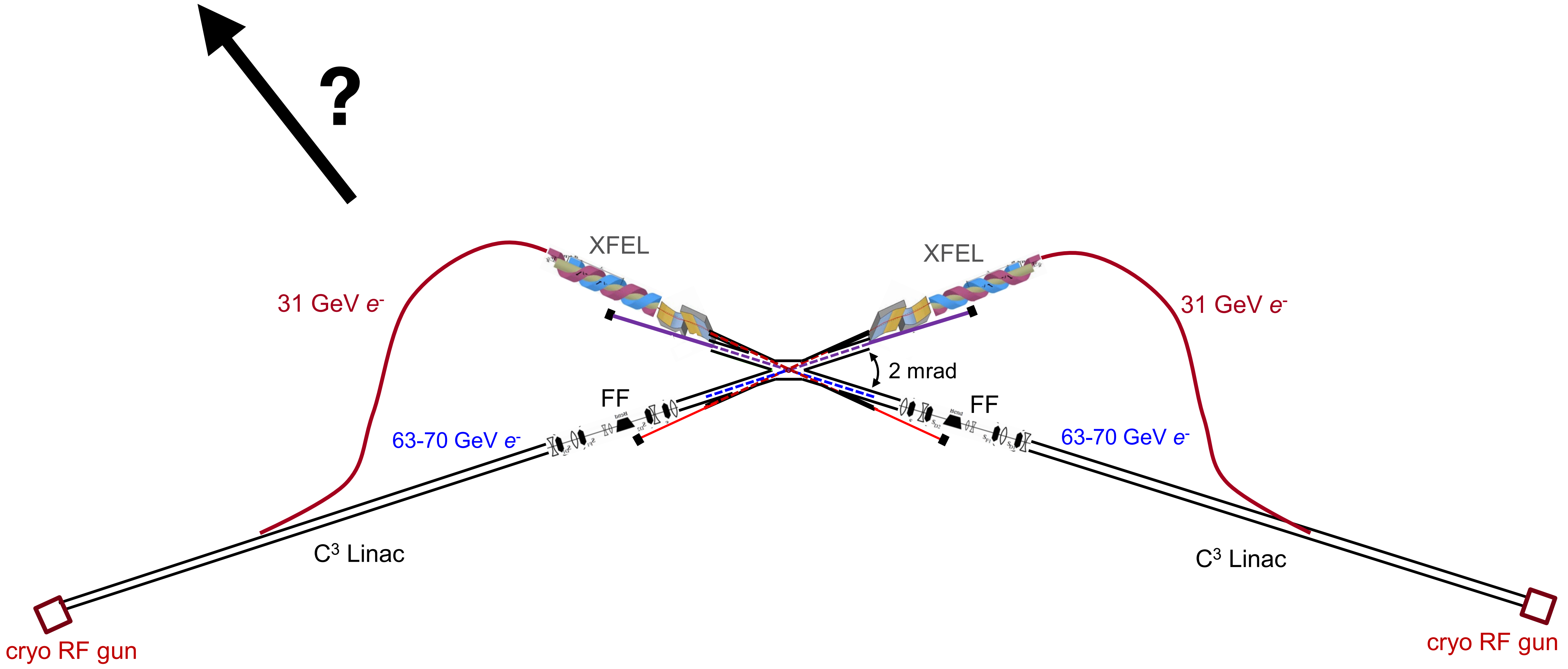
Upgrade: **TeV γ–γ collider** *(optical laser version)*



- Collide high-energy γ beams (*up to 1 TeV c.o.m. with original HALHF scheme*)
- γ produced from Compton backscattering off lasers
- 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)*





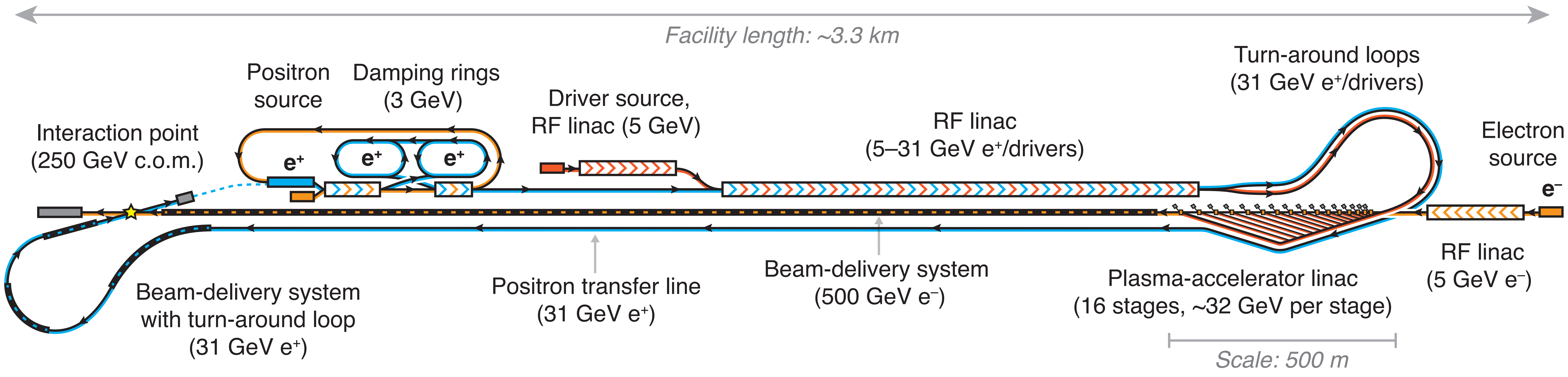
XCC: An X-ray FEL-based γγ Collider Higgs Factory
Barklow et al., arXiv:2203.08484 (2022)

- New concept from C3/SLAC colleagues
  - Use X-rays instead of optical laser
- 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*

Conclusions — HALHF

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

- **The HALHF concept proposes a compact, cheaper, greener, possibly quicker Higgs factory**
- **HALHF benefits from maximal asymmetry:** energy — charge — emittance
- **Upgrade path to higher energy and output:** not just a one-trick pony!
- **Challenges outlined by the community identify issues requiring more R&D** and help guide design decisions towards HALHF 2.0
- **Continued community engagement required to discuss and conclude on the path forward towards a pre-CDR**



Come and join us…

remote participation still possible

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

HALHF Workshop – Oslo, Norway

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

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- Registration
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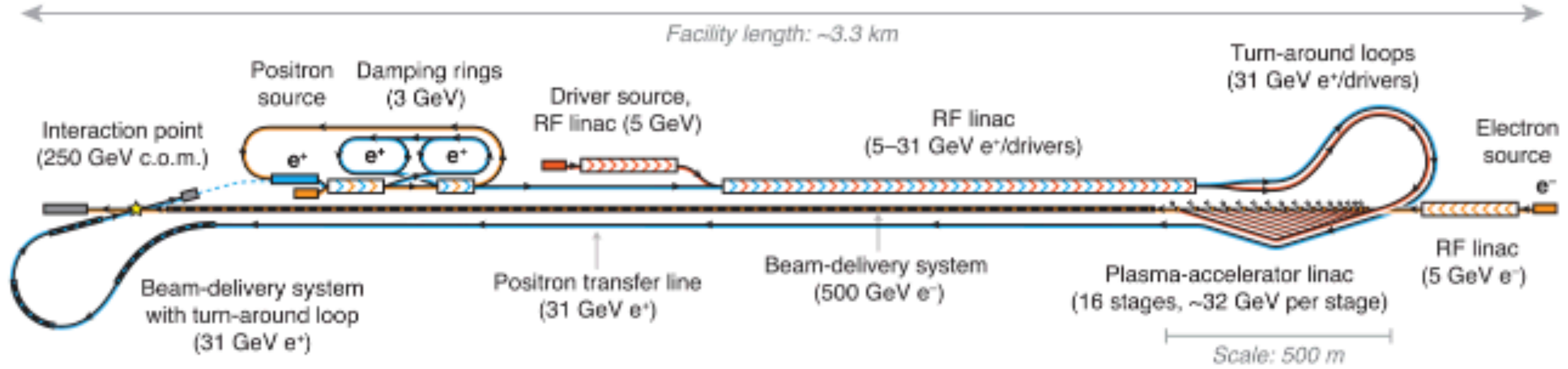
- Sightseeing in Oslo
- Travel information
- Committees

HALHF: "A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration" – B. Foster *et al.*, *New J. Phys.* 25 093037 (2023)



Welcome to Oslo, Norway!

Let's continue the discussion on HALHF and how to make it a reality.