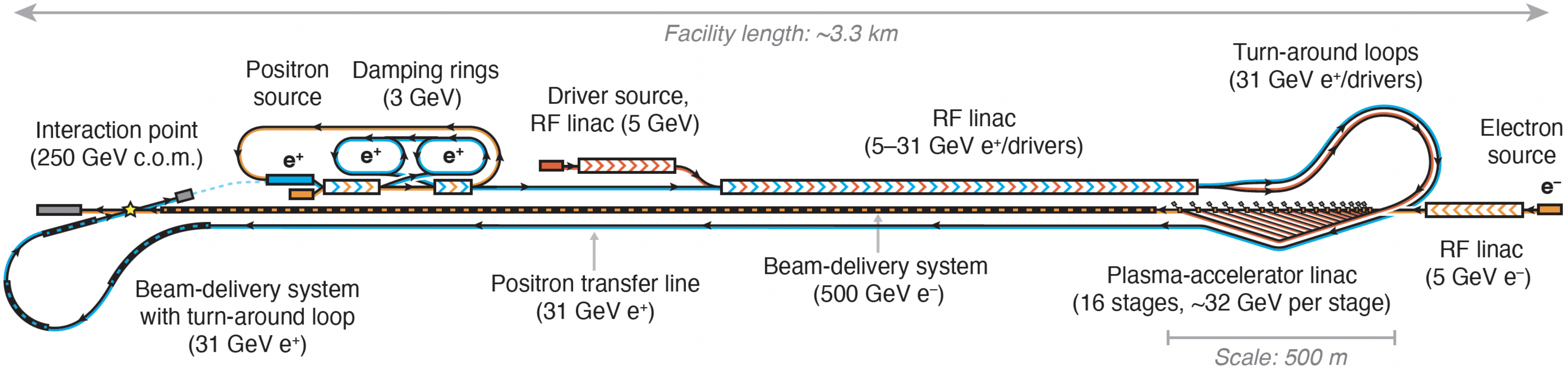
Hybrid Asymmetric Linear Higgs Factory (HALHF)

B. Foster, R. D'Arcy & C.A. Lindstrøm



Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)
Lindstrøm, D'Arcy and Foster, arXiv:2312.04975

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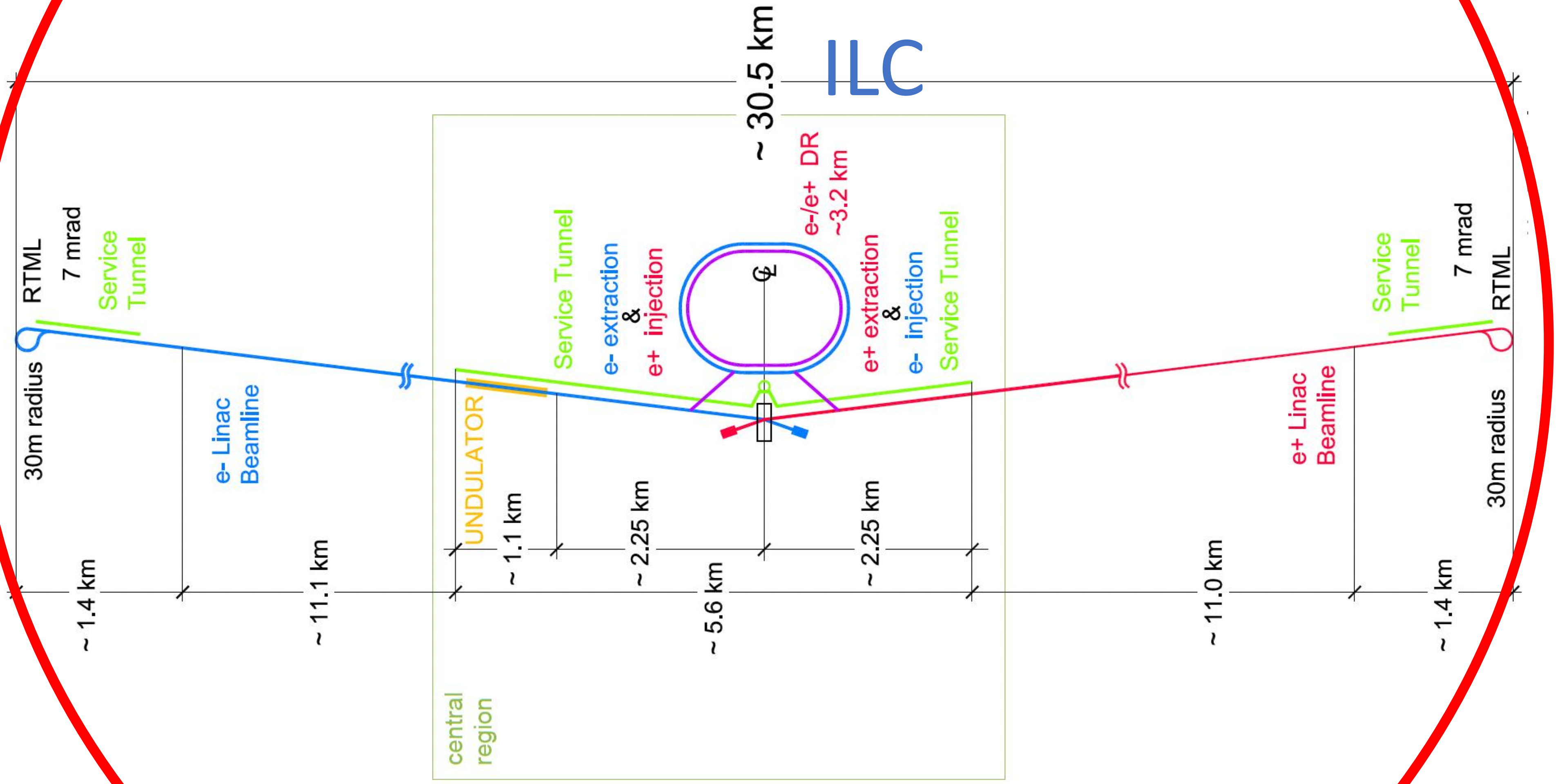
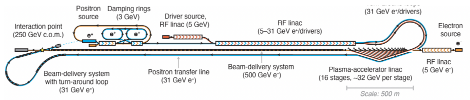


CEPC



https://arxiv.org/2303.10150

Hybrid Asymmetric Linear Higgs Factory (HALHF)

- For decades plasma acceleration has promised very high gradients => cheap LCs. HALHF for first time tries to make this a reality.
- The basic idea is – there are enough problems with a PWFA e^- accelerator; e^+ is even more difficult. Bypass this for e^+e^- collider by using conventional linac for e^+.
- For this to be attractive financially, conventional linac must be low energy => asymmetric energy machine.
- This requirement led to (at least for us) unexpected directions – the more asymmetric the machine became, the better!

Relativistic Refresher

$$E_e E_p = s/4 \quad (1)$$

and

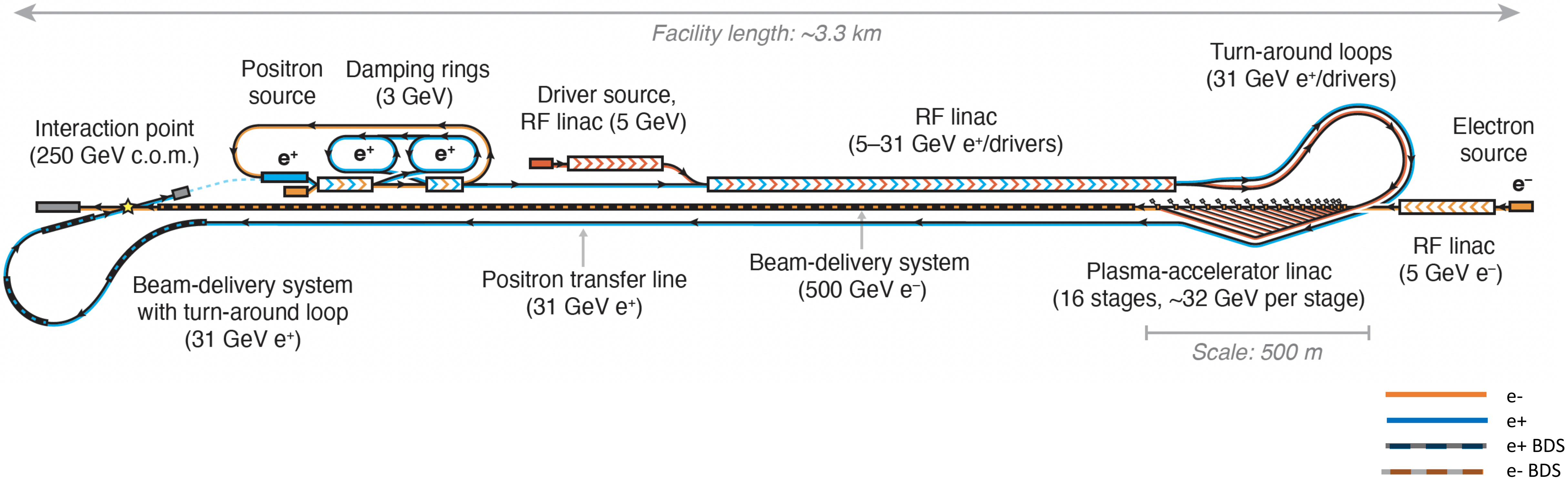
$$E_e + E_p = \gamma\sqrt{s}, \quad (2)$$

where E_e and E_p are the electron and positron energies, respectively, govern the kinematics. These two equations link three variables; fixing one therefore determines the other two. For a given choice of positron and centre-of-mass energy, the boost becomes

$$\gamma = \frac{1}{2}\left(\frac{2E_p}{\sqrt{s}} + \frac{\sqrt{s}}{2E_p}\right). \quad (3)$$

- It turns out that the (an) optimum (see below) for E_{cm} = 250 GeV is to pick E_e = 500 GeV, E_p= 31 GeV, which gives a boost in the electron direction of γ ~ 2.13.

HALHF Layout



- Overall facility length ~ 3.3 km – which will fit on ~ any of the major (or even ex-major) pp labs. (NB. A service tunnel a la ILC is costed but not shown)

Cost Estimate

Rough cost estimates for HALHF

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

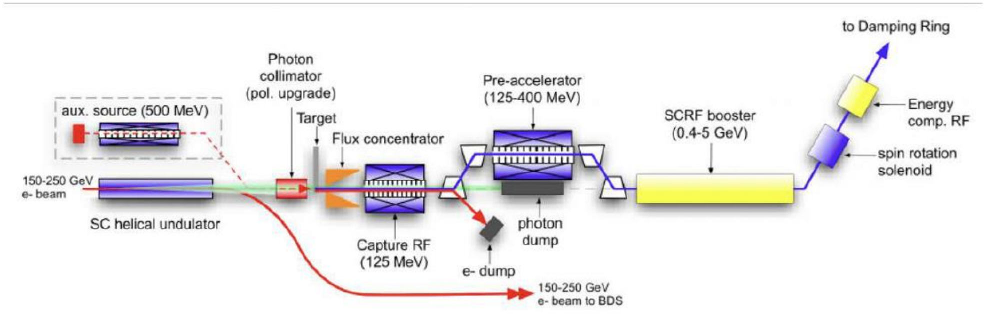
Subsystem	Original cost (MILCU)	Comment	Scaling factor	HALHF cost (MILCU)	Fraction
Particle sources, damping rings	430	CLIC cost [76], halved for e^+ damping rings only[a]	0.5	215	14%
RF linac with klystrons	548	CLIC cost, as RF power is similar	1	548	35%
PWFA linac	477	ILC cost [46], scaled by length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

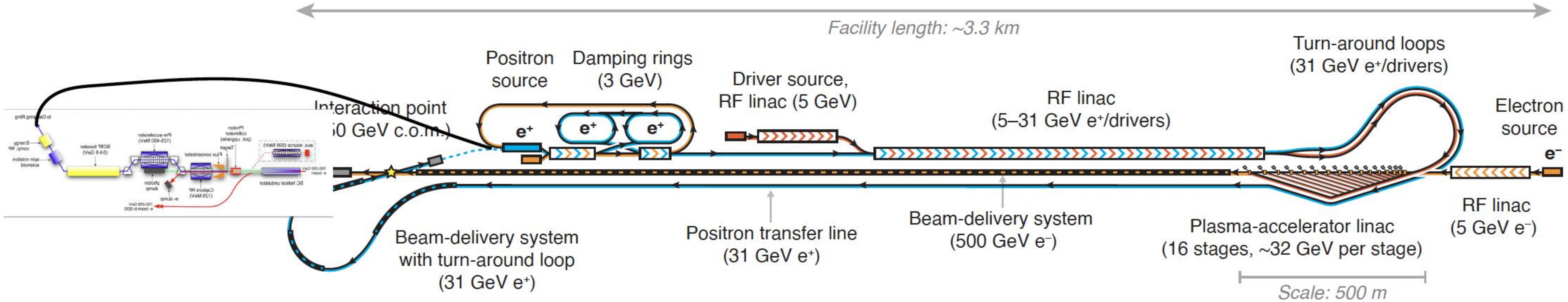
- Estimated **power usage is ~100 MW** (similar to ILC and CLIC):
  - 21 MW beam power + 27 MW losses + 2×10 MW damping rings + 50% for cooling/etc.

Outline of Upgrade Suite

- See [Lindstrøm, D'Arcy and Foster, arXiv:2312.04975]
- Polarised e^+

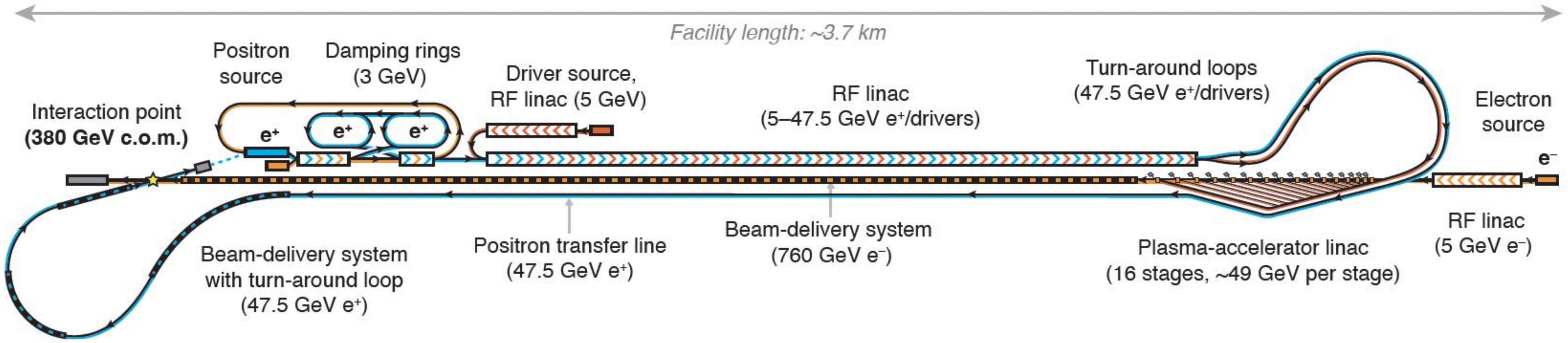
> Produce e+ polarization via ILC-like scheme:
>> ideas exist for E(e-) 500 GeV
>> wiggler probably longer and more expensive.





Outline of Upgrade Suite

- Energy upgrade to ttbar (380 GeV) => 47.5 GeV positrons / 760 GeV electrons (same # of stages, same boost).



- => +130 m PWFA linac; added cost ~23%; >~25% more power.

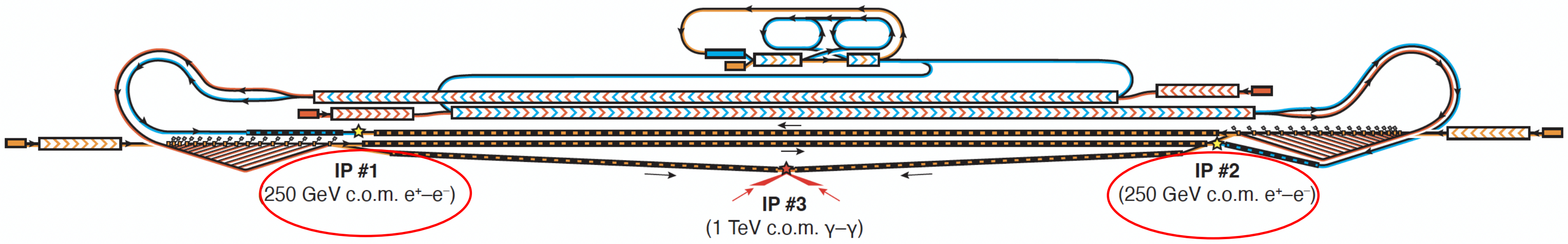
Outline of Upgrade Suite

- Energy upgrade to Higgs self-coupling, ttH Yukawa (550 GeV).

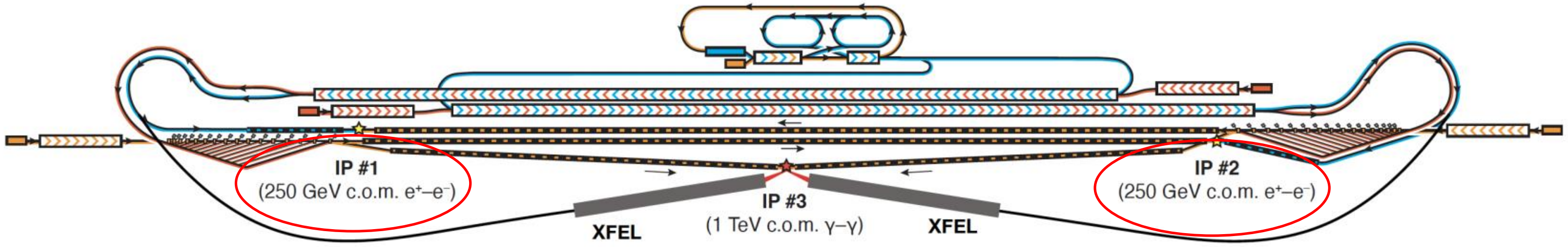
- 68.5 GeV positrons / 1.1 TeV electrons(same # of stages, same boost, plasma cell length increased to 11m);
- => RF linac more than doubled in length – 2.75 km;
- +254 m PWFA linac;
- Roughly 48% increase in cost cf Higgs factory; power increases by 90 MW to 190 MW.
- Add 2nd IP for any energy – costs 20% - 44% more.

Outline of Upgrade Suite

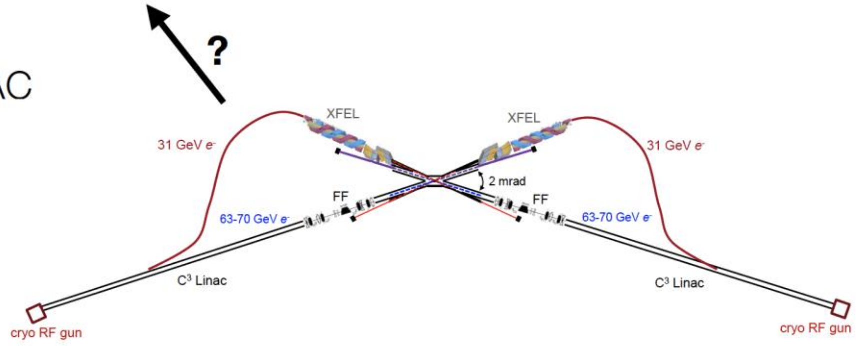
- $\gamma\gamma$.



Upgrades: **Gamma–gamma collider** *(XFEL version)*



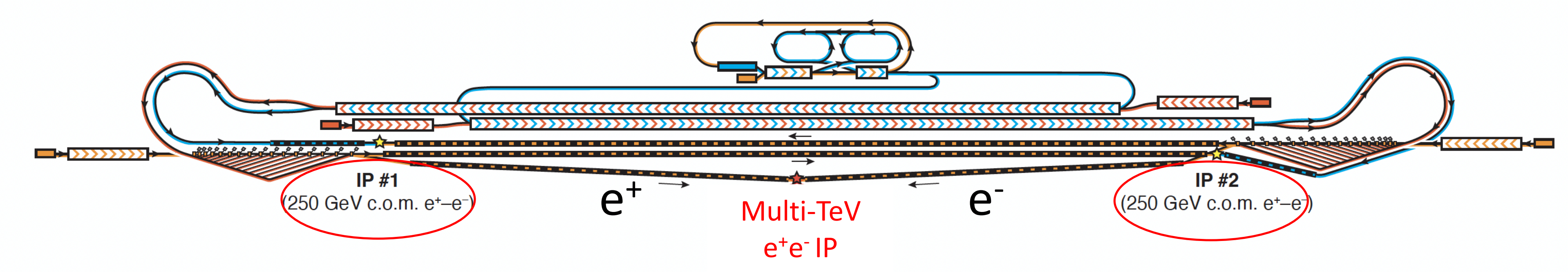
- New concept from our friends from C3/SLAC
  - Use X-rays instead of optical laser
- Somewhat advanced, but has benefits: we already have the high-power source.
- Would be the most powerful XFELs ever: Photon scientists may wish to collaborate.



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

Outline of Upgrade Suite

- Multi-TeV;
- Requires solution of positron acceleration in plasma;
- Return to symmetric accelerator.



Upgrade Summary

Upgrade	*Additional cost (MILCU)*	*Fraction of original HALHF cost*
Polarised positrons	185	12%
$t\bar{t}$ threshold (380 GeV c.o.m.)	350	23%
Higgs self-coupling (550 GeV c.o.m.)	750	48%
Two IPs	300	19%
Two IPs + additional linac	689	44%
Two IPs + additional linac & positron source	804	52%
γ–γ collider (laser-based)	250	17%
e^+–e^- collider, symmetric (assuming e^+ PWFA)	$\sim$0	$\sim$0

Table 2. Estimated cost of upgrades discussed in the text. The final two upgrades require the "Two IPs + additional linac & positron source" upgrade to have already been carried out.

Current Status

- HALHF Collaboration "kick-off" meeting @ DESY 23/10/23. Attendance ~ 50.

Monday, 23 October 2023, 13:00-22:00 (incl. dinner)

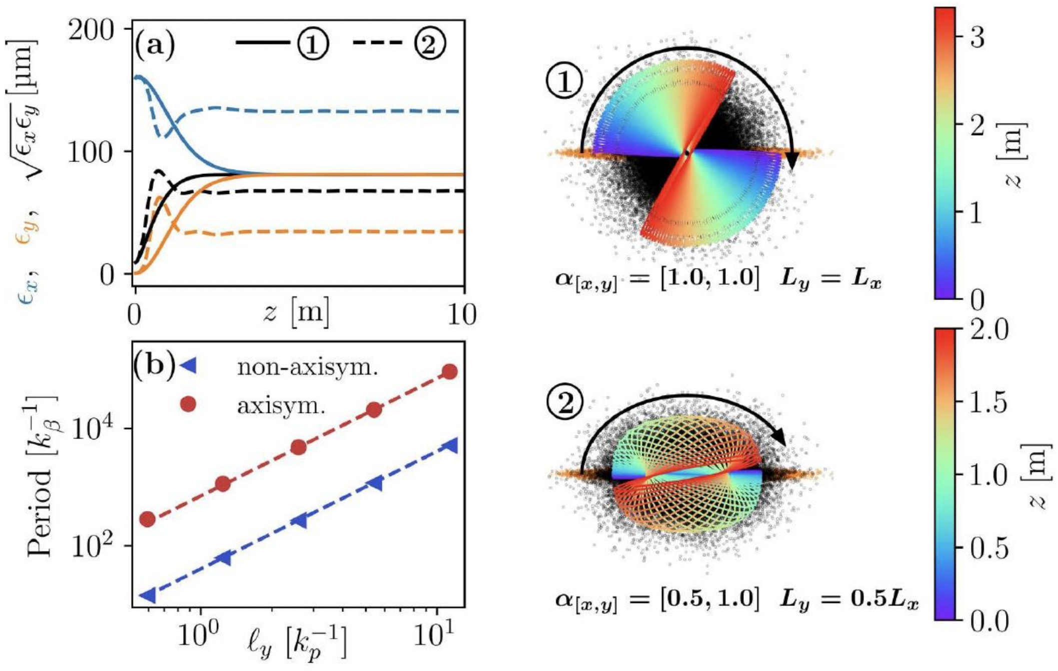
13:00			*HARBOR (Building 610, seminar room) or Zoom*
13:00	10'	Wim Leemans	Global considerations
HALHF introduction and status			
13:10	10'	Brian Foster	General introduction to HALHF
13:20	40'	Carl Lindstrøm	Proposed design, recent developments and upgrades
13:50	10'	Richard D'Arcy	Project staging / demo facilities (R&D milestones)
14:10	30'	All	Open discussion
R&D for HALHF			
14:40	35'	Jenny List	Physics and detector systems for HALHF
15:15	*30'*		*Coffee break*
15:45	60'	Assessment of challenges for the conventional systems	
	10' 10' 10' 10'	Nick Walker Nick Walker & Steffen Doebert Gudrid Moortgat-Pick Spencer Gessner	Introduction Linacs Positron source Beam delivery system
	20'	All	Open discussion
16:45	60'	Assessment of challenges for plasma systems	
	5' 15' 5' 15'	Richard D'Arcy Erik Adli Kris Põder Richard D'Arcy	Introduction High beam energy and quality Spin polarisation High beam power
	20'	All	Open discussion
17:45	15'	Brian Foster, Wim Leemans	Wrap-up and next steps
18:00			*Continued discussions (with pizza dinner and drinks)*
22:00		*Adjourn*	

- HALHF Workshop @ Oslo 4-5/4/24. Attendance ~ 30 (physical+ Zoom).

https://indico.cern.ch/event/1370201/

Selected Updates

- PWFA arm:
  - Flat beams (essential to get required lumi at IP while minimising beamsstrahlung)
    - "Resonant emittance mixing of flat beams in plasma accelerators"
      S. Diederichs et al., arXiv:2403:05871
    - Issue: when ion motion present, non-linear focusing mixes planes
    - => Flat beams don't stay flat
    - Possible solution: flat drive beams
    - Seems to work – but need to evaluate ion-motion from witness beam



Source: Diederichs et al., preprint arXiv:2403.05871 (2024)

Parameter Optimisation

- A “simple” cost model for optimization
- > Need to implement sufficient complexity for all parameters to have high-cost extrema:
- > Example:
  - Low rep. rate — long runtime = high cost of constant-power overheads
  - High rep. rate — high peak power = high cost of power infrastructure
- > Currently implemented (analytic only, no simulation):
- > RF linacs (voltage limited by power and BDR, efficiency based on filling time/cooling)
- > Damping rings (radius based on bunch-train length, damping-time limits, rep rate)
- > Plasma linac (lengths and efficiencies, but not yet effect on emittance)
- > PWFA emittance growth due to instabilities (model by Lebedev et al.)
- > + turnarounds, BDS, tunnels, power infrastructure, general overheads, dumps

Parameter Optimisation

- Also indicates that separating positron and drive-beam acceleration may be advantageous both for flexibility and cost – but still exploring;
- Also reduced energy asymmetry may be better – still exploring this too
- Comprehensive simulation campaign using
  - plasma density $1*10^{15}$.
  - Gradient: 2 GV/m.
  - Efficiency: ~35% wake-to-beam efficiency, driver depletion efficiency 75–80%
  - Electron charge still about 1.6 nC. Driver charge around 8 nC. Transformer ratio ~1.5 (somewhat shaped/triangular driver)

Status of "Conventional" Arm

- Working Groups for:
- Linac; Polarisation in PWFA; Positron Source; BDS
- Others required: Damping Rings, overall Beam Dynamics & machine lattice, etc.
- Limited by lack of any funding! CAL ERC Grant only explicit support
- Linac: both CW SCRF and warm L-band linacs seem possible, although difficult. "Combined function" also seems possible, although separated function would be advantageous if affordable – optimisation tool! Cost will rise significantly!

Summary & Outlook

- HALHF is not just a Higgs Factory
- Work on optimizing parameters underway – changes coming!
- Regular monthly HALHF accelerator meetings
- In parallel, physics & detector studies continue, coordinated by J. List.
- Oslo Workshop in April; working towards next workshop in Erice, 3-8.10.24
- Short-term goal: “pre-CDR” input to European Strategy and to comprehensive global LC plan.
- Longer-term goal: funding required to start R&D programme

Backup Slides

HALHF Parameter Table

Machine parameters	*Unit*	*Value*	
Center-of-mass energy	GeV	250	
Center-of-mass boost		2.13	
Bunches per train		100	
Train repetition rate	Hz	100	
Average collision rate	kHz	10	
Luminosity	$cm^{-2}\,s^{-1}$	0.81×10^{34}	
Luminosity fraction in top 1%		57%	
Estimated total power usage	MW	100	
Colliding-beam parameters		e^-	e^+
Beam energy	GeV	500	31.25
Bunch population	10^{10}	1	4
Bunch length in linacs (rms)	μm	18	75
Bunch length at IP (rms)	μm	75	
Energy spread (rms)	%	0.15	
Horizontal emittance (norm.)	μm	160	10
Vertical emittance (norm.)	μm	0.56	0.035
IP horizontal beta function	mm	3.3	
IP vertical beta function	mm	0.1	
IP horizontal beam size (rms)	nm	729	
IP vertical beam size (rms)	nm	7.7	
Average beam power delivered	MW	8	2
Bunch separation	ns	80	
Average beam current	μA	16	64

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
PWFA linac and drive-beam parameters		
Number of stages		16
Plasma density	cm^{-3}	7×10^{15}
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	42
Driver average beam power	MW	21.4
Driver bunch separation	ns	5
Driver-to-wake efficiency	%	72
Wake-to-beam efficiency	%	53
Driver-to-beam efficiency	%	38
Wall-plug-to-beam efficiency	%	19
Cooling req. per stage length	kW/m	100

[a] The first stage is half the length and has half the energy gain of the other stages (see Section V. 4).

HALHF Parameters cf ILC & CLIC

Parameter	*Unit*	*HALHF*		*ILC*	*CLIC*
		e^-	e^+	e^-/e^+	e^-/e^+
Center-of-mass energy	GeV	250		250	380
Center-of-mass boost		2.13		-	-
Bunches per train		100		1312	352
Train repetition rate	Hz	100		5	50
Average collision rate	kHz	10		6.6	17.6
Average linac gradient	MV/m	1200	25	16.9	51.7
Main linac length	km	0.41	1.25	7.4	3.5
Beam energy	GeV	500	31.25	125	190
Bunch population	10^{10}	1	4	2	0.52
Average beam current	µA	16	64	21	15
Horizontal emittance (norm.)	µm	160	10	5	0.9
Vertical emittance (norm.)	µm	0.56	0.035	0.035	0.02
IP horizontal beta function	mm	3.3		13	9.2
IP vertical beta function	mm	0.1		0.41	0.16
Bunch length	µm	75		300	70
Luminosity	$\mathrm{cm^{-2}\ s^{-1}}$	0.81×10^{34}		1.35×10^{34}	2.3×10^{34}
Luminosity fraction in top 1%		57%		73%	57%
Estimated total power usage	MW	100		111	168
Site length	km	3.3		20.5	11.4