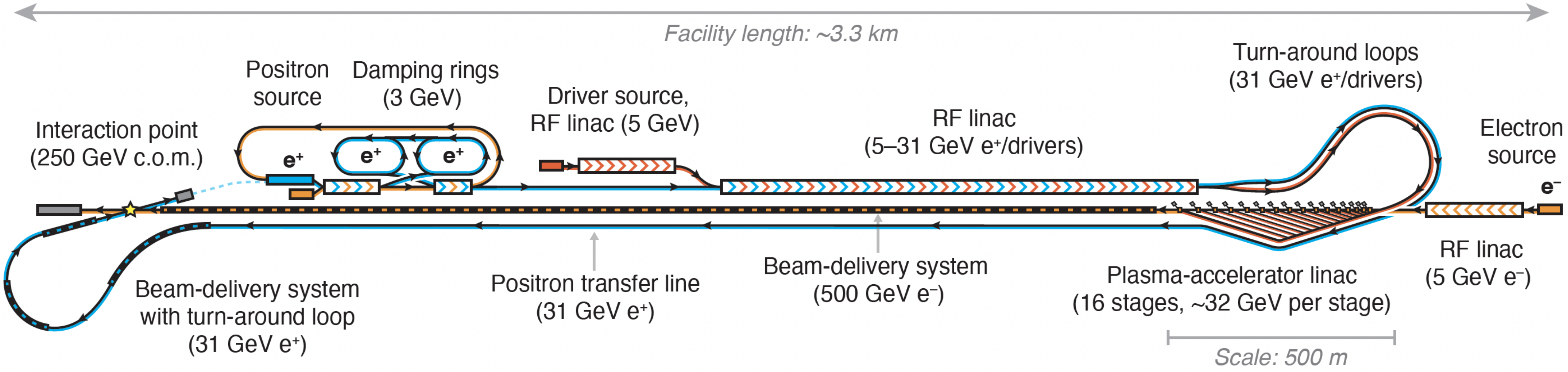
Hybrid Asymmetric Linear Higgs Factory (HALHF)

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

Hybrid Asymmetric Linear Higgs Factory (HALHF)

- 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

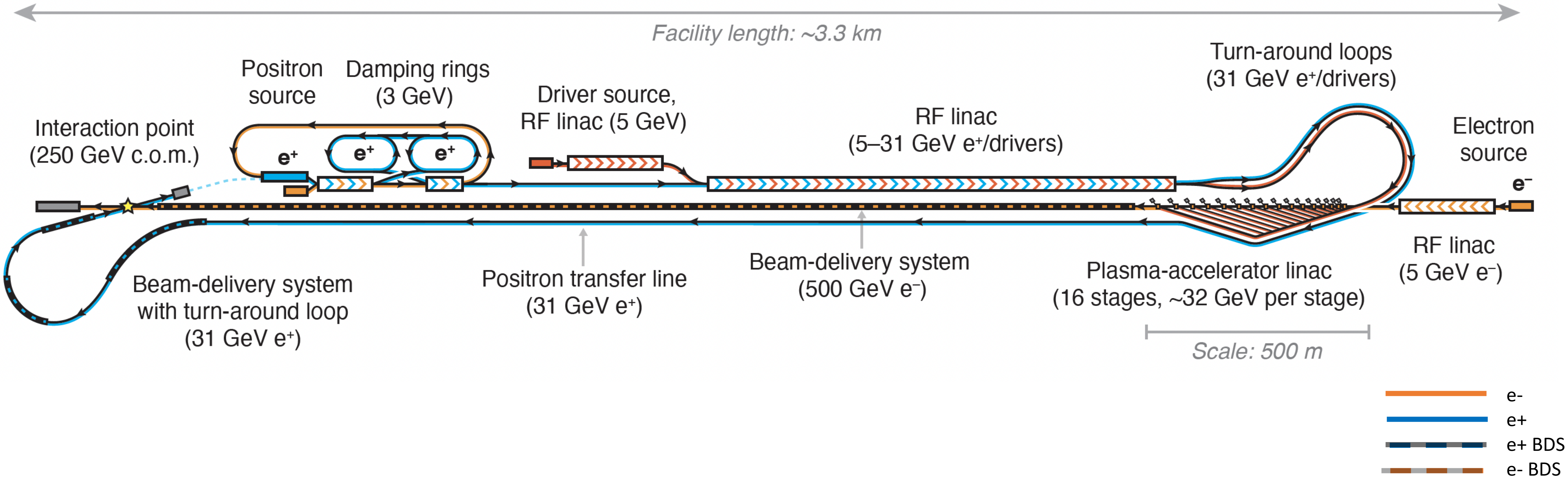
$$E_e + E_p = \gamma\sqrt{s}, \quad (2)$$

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)

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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).

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.

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Status

- HALHF Collaboration "kick-off" meeting at DESY on 23/10/23.

Attendance ~ 50.

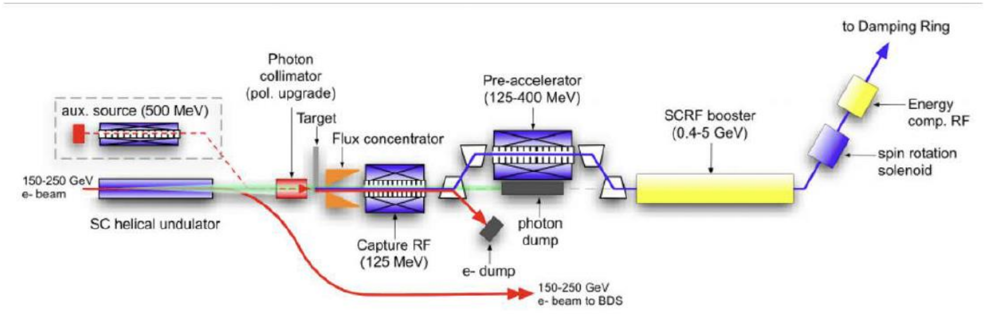
Monday, 23 October 2023, 13:00-22:00 (incl. dinner)

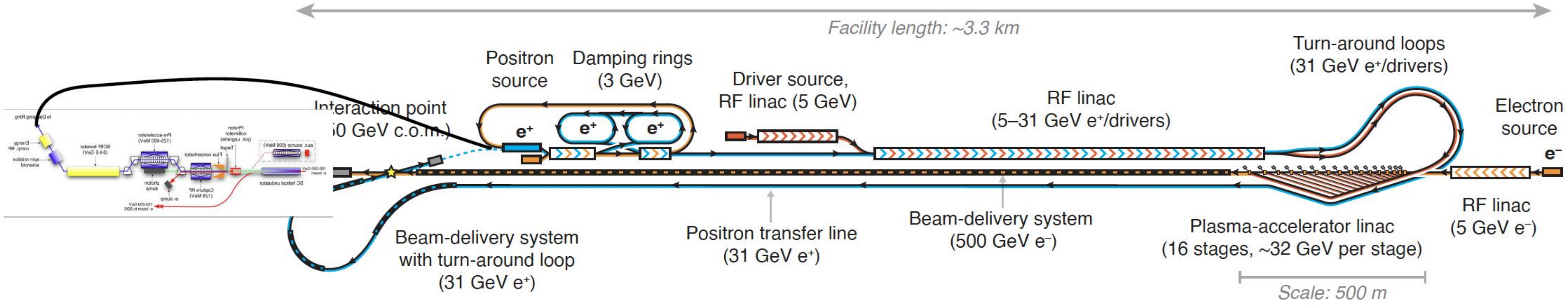
13:00			*HARBOR (Building 610, seminar room) or Zoom*
13:00	10'	Wim Leemans	Global considerations
HALHF introduction and status			
13:10	10'	Brian Foster	General introduction to HALHF
13:20	40'	Carl Lindstrøm	Proposed design, recent developments and upgrades
13:50	10'	Richard D'Arcy	Project staging / 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*	

Outline of Upgrade Suite

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

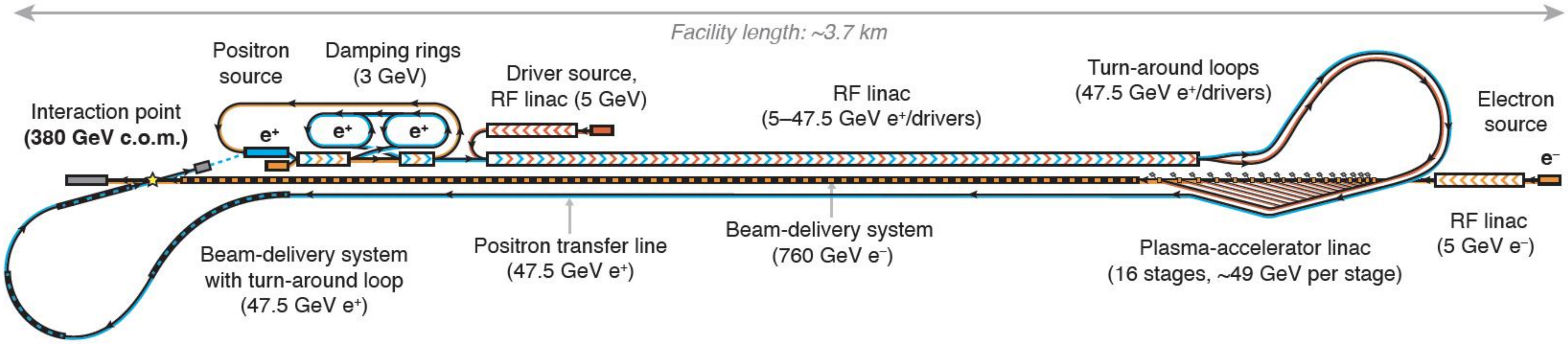
> Produce e+ polarization via ILC-like scheme:
>> ideas exist for E(e-) 500 GeV
>> wiggler probably longer and more expensive.





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

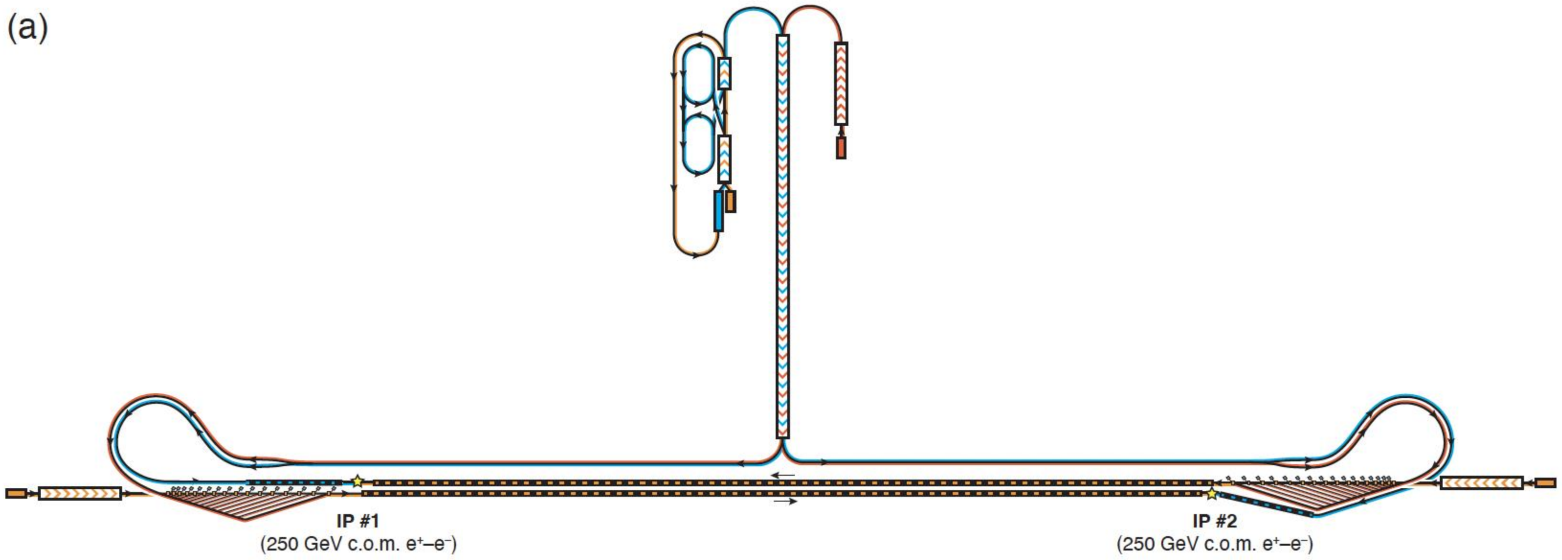
- Energy upgrade to Higgs self-coupling, ttH Yukawa (550 GeV).

- 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.

Outline of Upgrade Suite

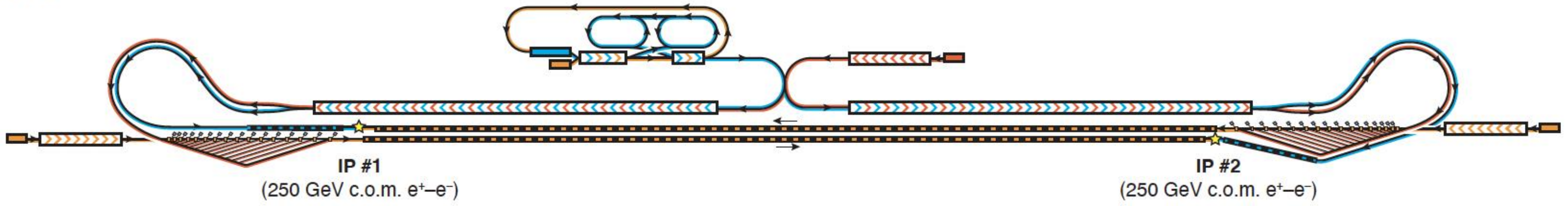
- Two IPs.

(a)



- a) I-shape

(b)

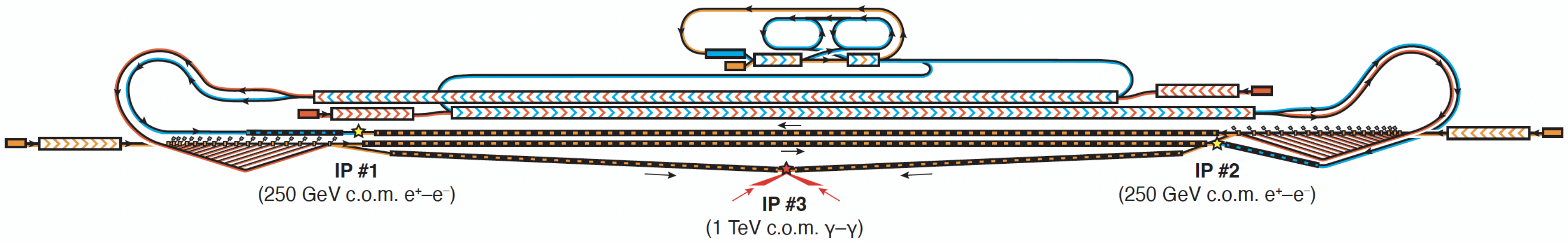


- b) 2 Linac

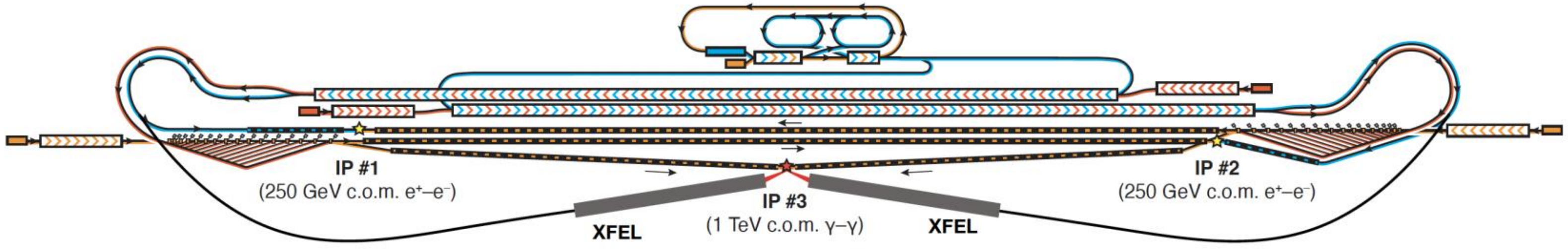
- a) ~ 20% cost increase; b) 44%

Outline of Upgrade Suite

- γγ.



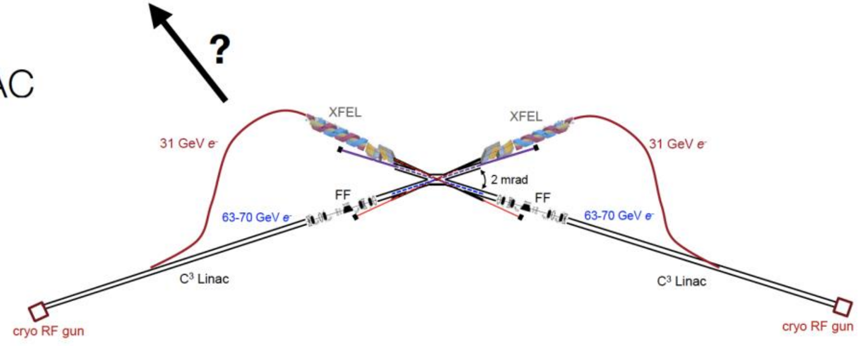
Upgrades: **Gamma–gamma collider** *(XFEL version)*



> New concept from our friends from C^3/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)

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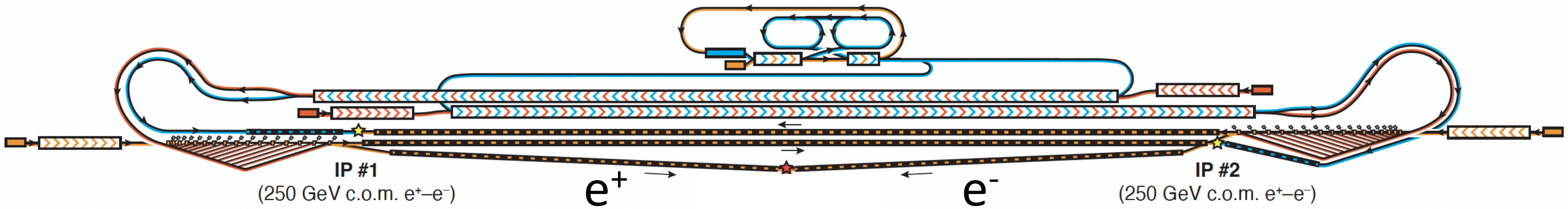
Outline of Upgrade Suite

- Multi-TeV
- Requires solution of positron acceleration in plasma



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Upgrade Summary

- Multi-TeV

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.

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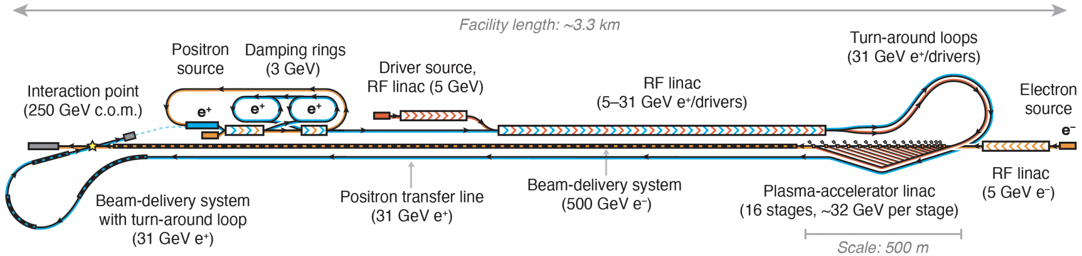
Status of PWFA arm

- Work ongoing in Oslo:
  - Preliminary simulations: Transverse (beam-breakup) instabilities;
  - Preliminary simulations: Effect of (betatron) radiation reaction;
  - Preliminary simulations: Coupling of multiple PWFA stages.
- Also simulation work going on in DESY on beam ionization/ion motion (S. Diederichs, M.Thévenet)
- Parameters will change - watch this space!

Status of “Conventional” Arm

- Some Working Groups formed:
- Linac: (S. Ackermann), S. Doebert, B. List, N. Walker,
- Polarisation in PWFA: K. Poeder
- Positron Source: G. Moortgat-Pick et al.
- BDS: A. Seryi, S. Gessner
- Need others, particular Damping Rings, overall Beam Dynamics & machine lattice, etc.
- Limited by lack of visible funding!

Summary & Outlook



- HALHF is not just a Higgs Factory – more a way of life ☺
- Work on optimizing parameters underway – there will be changes!
- Task forces are meeting: first regular monthly HALHF accelerator meeting on Monday December 18th.
- In parallel, physics & detector studies continue and initiating regular monthly meetings. Coordinated by J. List.
- Plan Oslo Plenary in April 2024; Erice Plenary Week 3-8.10.24

Backup Slides

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	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

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