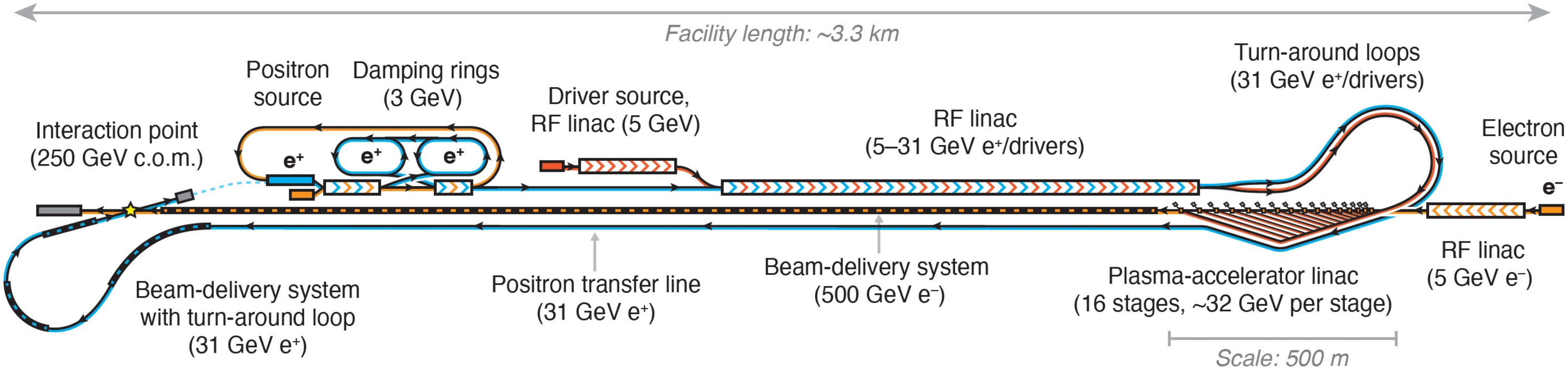
Hybrid Asymmetric Linear Higgs Factory (HALHF)

B. Foster, R. D'Arcy & C.A. Lindstrøm



https://arxiv.org/2303.10150

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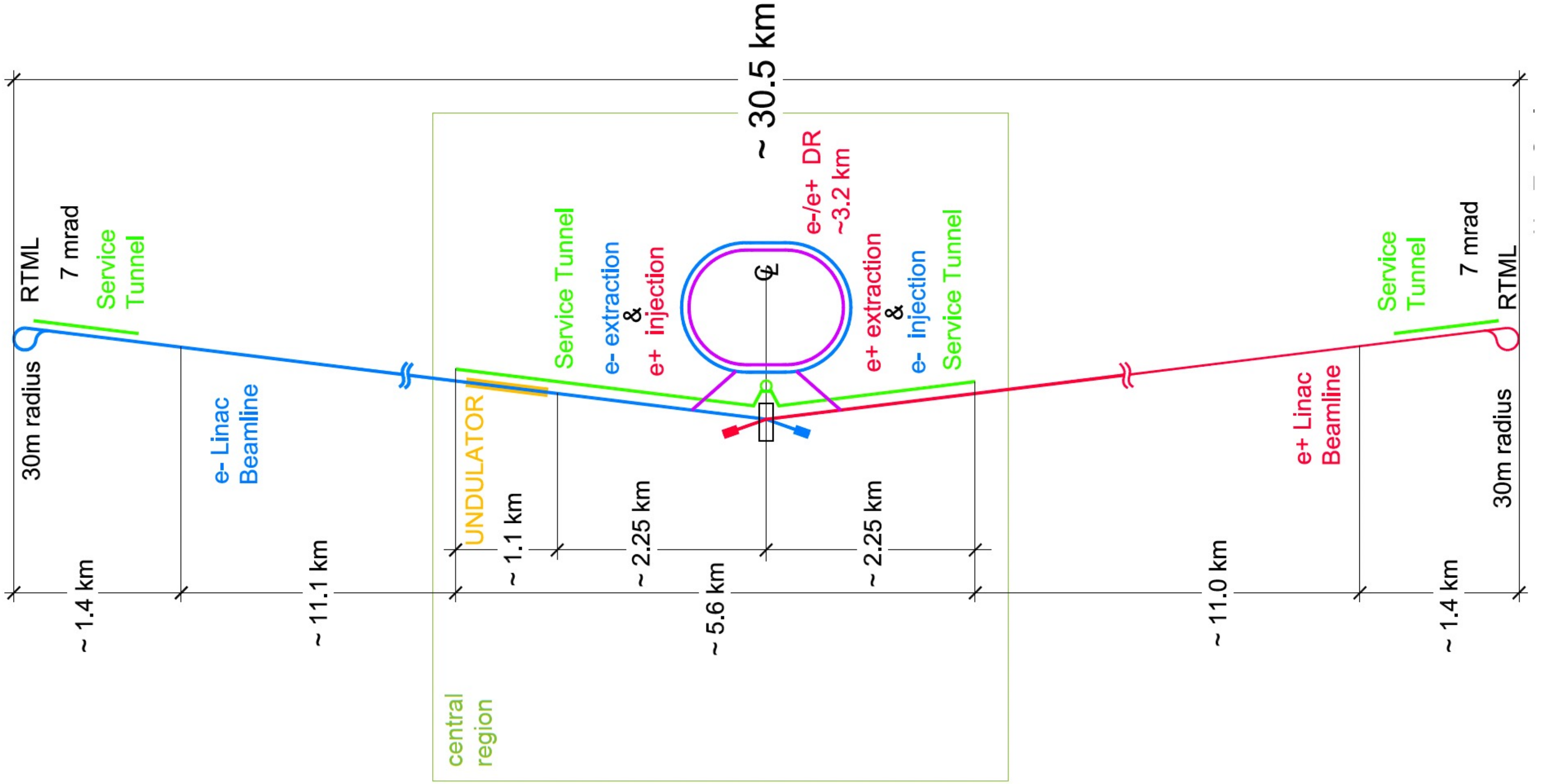
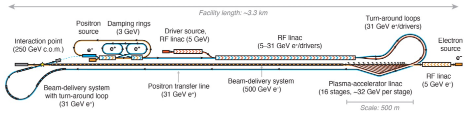
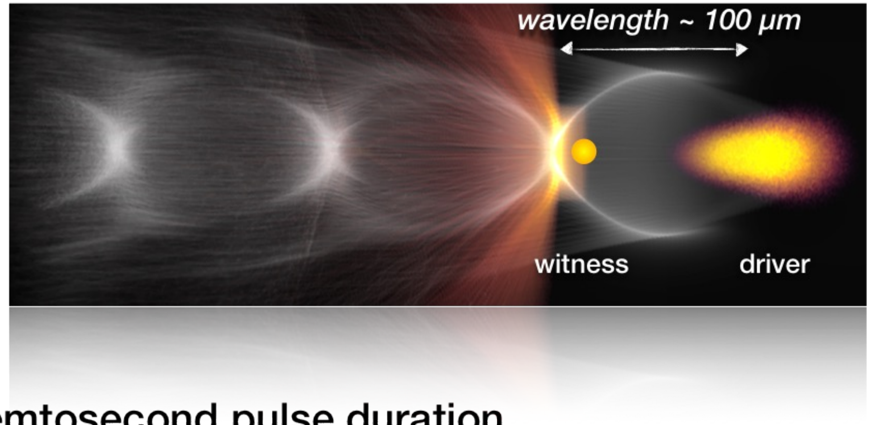




Plasma Wave Acceleration

Charge density wave in a plasma

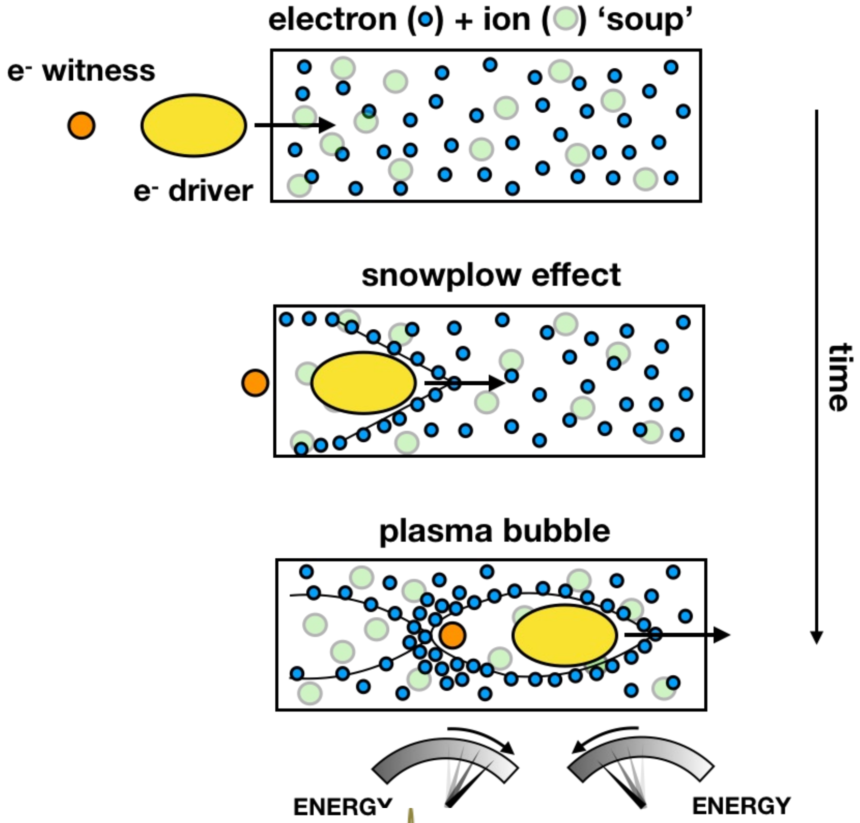


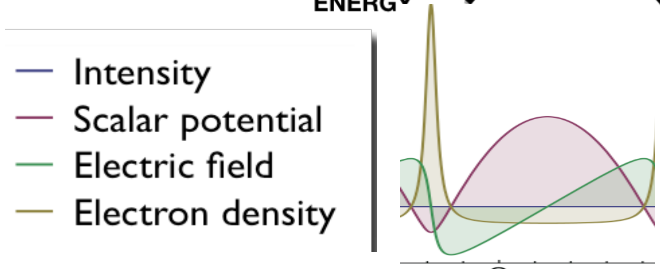
Femtosecond pulse duration

Intrinsically short due to short plasma wavelength

GV/m acceleration gradients

No surface quality limitations → **E_z in GV/m range**





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

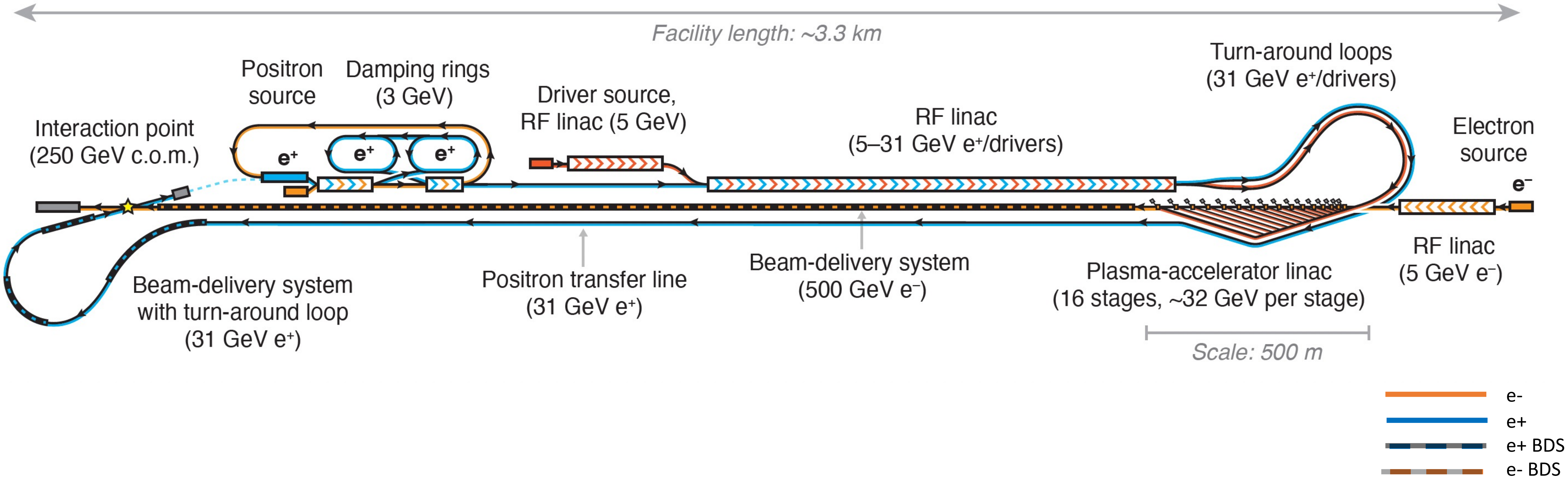
$$E_e + E_p = \gamma\sqrt{s}, \quad (2)$$

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)

Energy Efficiency

- Asymmetric machines less energy efficient than symmetric – energy lost "in accelerating the C.o.M." For equal bunch charges => 2.5 times more energy required for same C.o.M. energy.
- Can be reduced by introducing asymmetry into beam charges – increase charge of low-energy beam and decrease high-energy s.t. $N^2 = N_e N_p$ constant => $\mathcal{L}$ conserved.
- $P/P_0 = (N_e E_e + N_p E_p)/(N^* \mathrm{sqrt}(s))$
- Optimum is to scale e^+ charge by $\mathrm{sqrt}(s)/(2E_p)$, i.e. factor ~ 4.
- Producing so many e^+ problematic – compromise by scaling by factor 2 (2^*e^+, $½^*\ e^-$).
- Reduces energy increase to 1.25. Also reduces bunch charge in PWFA arm.

Emittance reduction

- Geometric emittance of bunch scales with 1/E .
- Lower-energy e^+ beam must have smaller β function at I.P. – use $\beta_x / \beta_y = 3.3/0.1$ mm c.f. CLIC 8.0/0.1 mm.
- In contrast, high-energy e^- beam - β function can be increased, which could reduce complexity of BDS.
- More interesting is to increase the e^- emittance AND reduce the β function => normalized emittance can be 16 times higher for the same $\mathcal{L}$ => increased tolerances in PWFA arm.
- Beam-beam focusing effect on $\mathcal{L}$ must be simulated with Guinea Pig.

Beam-beam Effects

- Guinea-Pig results:

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

- ILC

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- HALHF

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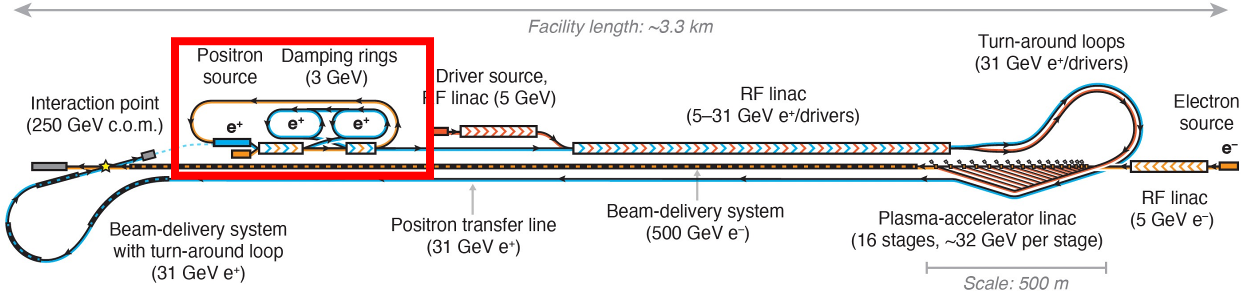
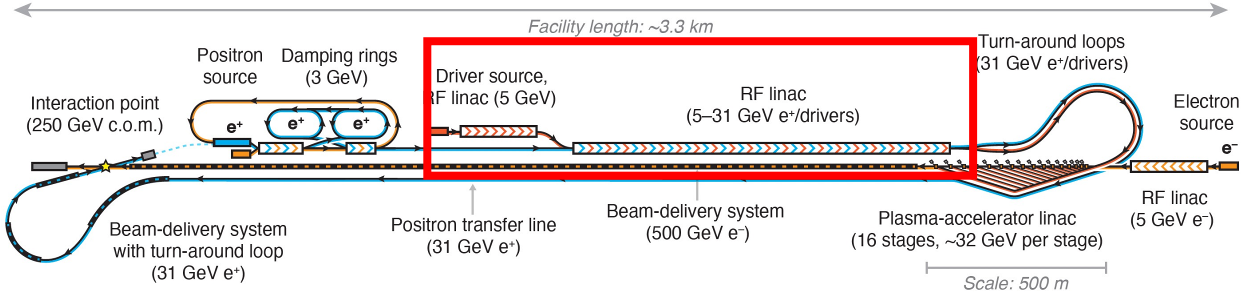
- ILC
- HALHF
- HALHF with reduced emittance for PWFA

Positron Source



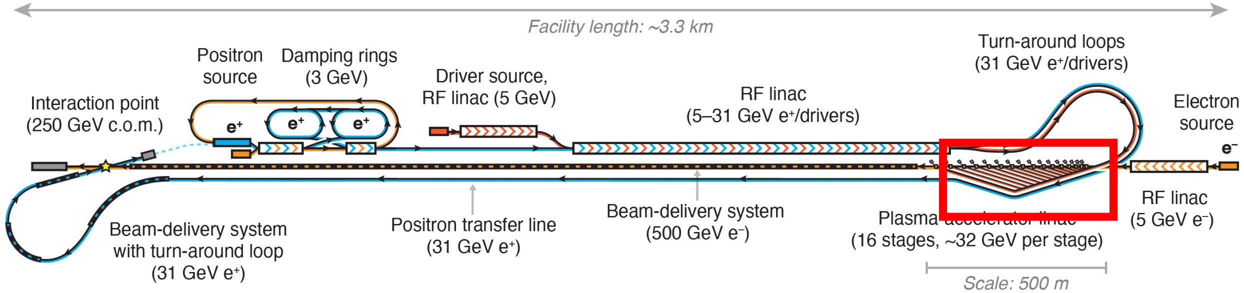
- "Conventional" e^+ sources are not trivial – that for ILC, which has relaxed requirements wrt HAHLF, still under development.
- e^- accelerated to 5 GeV and then collide with target to produce e+ which are accumulated, bunched and accelerated to 3 GeV and then damped in 2 rings (~identical to CLIC but bigger e^+ bunch charge ($4*10^{10}$ e^+).
- May be possible to use spent e^+ bunch after collision rather than dedicated e^- bunch, with cost savings.

Main RF Linac



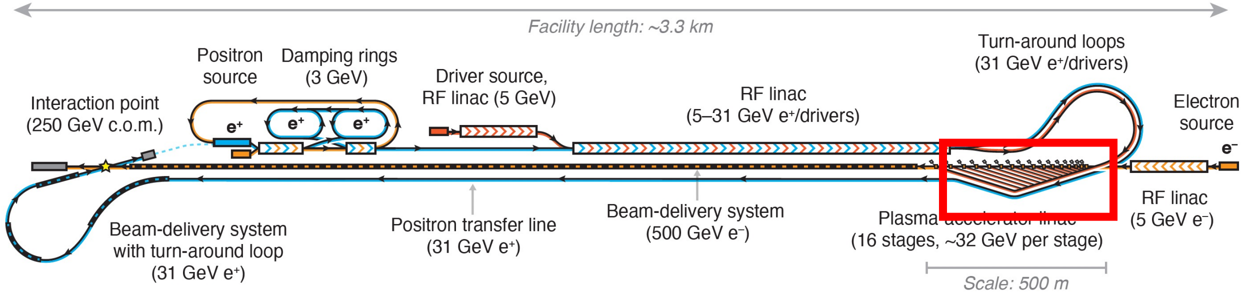
- Split in 2, to accelerate e^- PWFA drive beams from 1 – 5 GeV & then both e^+ and e^- from 5 GeV to 31.3 GeV.
- Assume gradient of 25 MV => 1.25 km long.
- Delivers total average power of 21.4 MW => including e^+ power and $\varepsilon \sim 50\%$, wall-plug 47 MW.
- Assume warm L-band linac – CW SRF could be used but would change bunch pattern.
- Before drivers, e^+ bunch accelerated with 180^o phase offset.

PWFA Linac



- Drivers go through turn-around and then distributed to plasma cells via undulating delay chicane.
- Assuming TR ~ 1, e- bunch accelerated by 31 GeV/5m stage => 16 stages with $\rho \sim 7*10^{15}$ => 6.4 GV/m.

PWFA Linac



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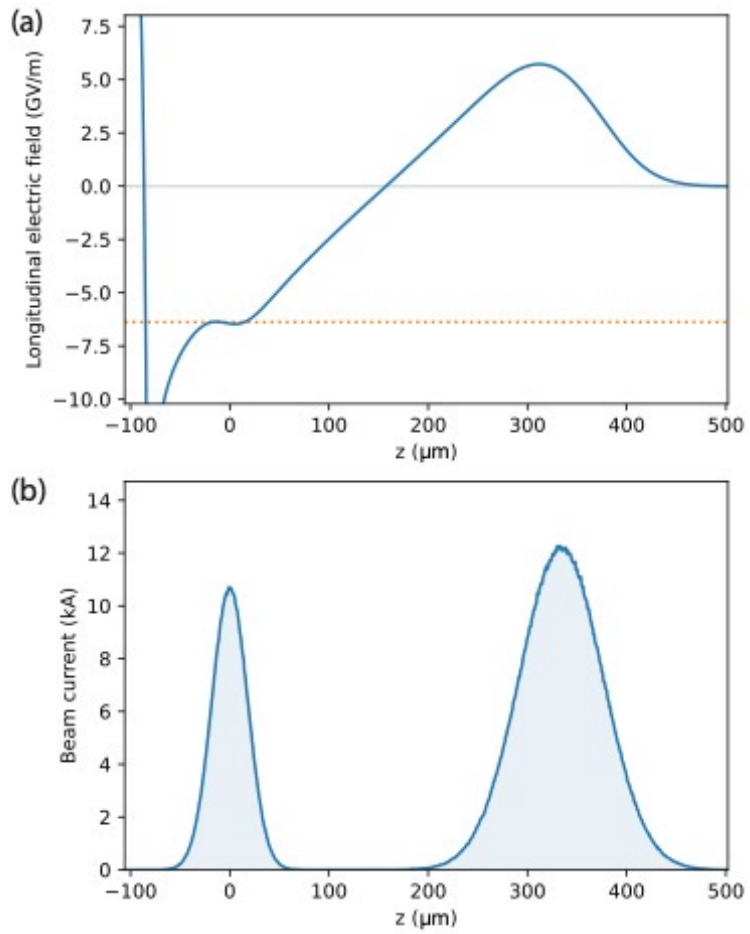

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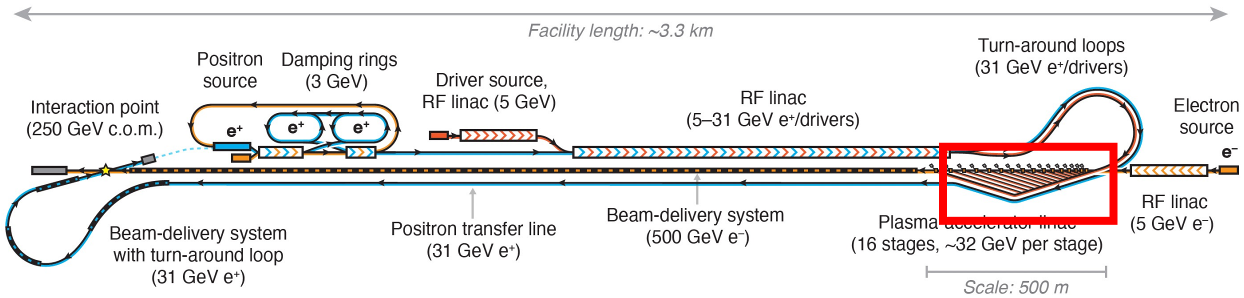
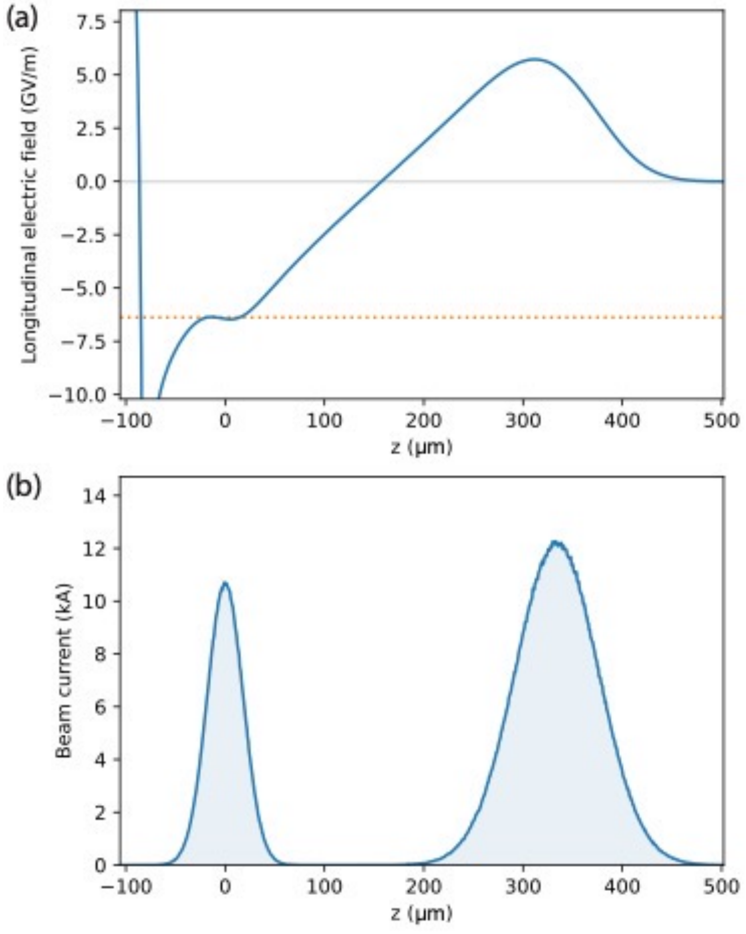
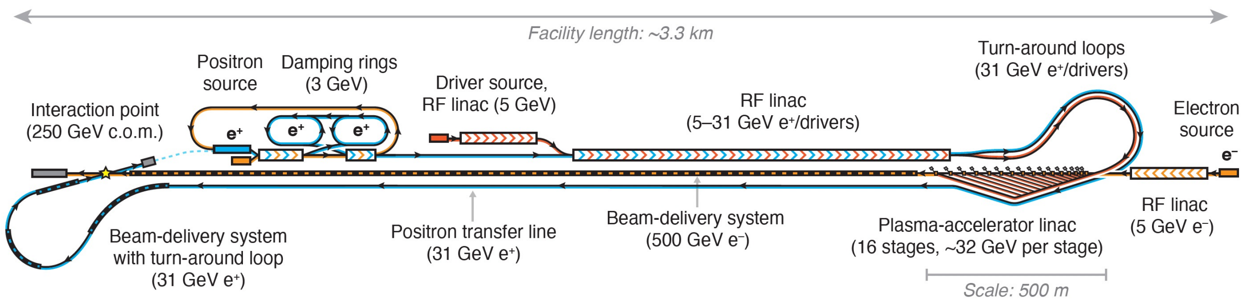
PWFA Linac



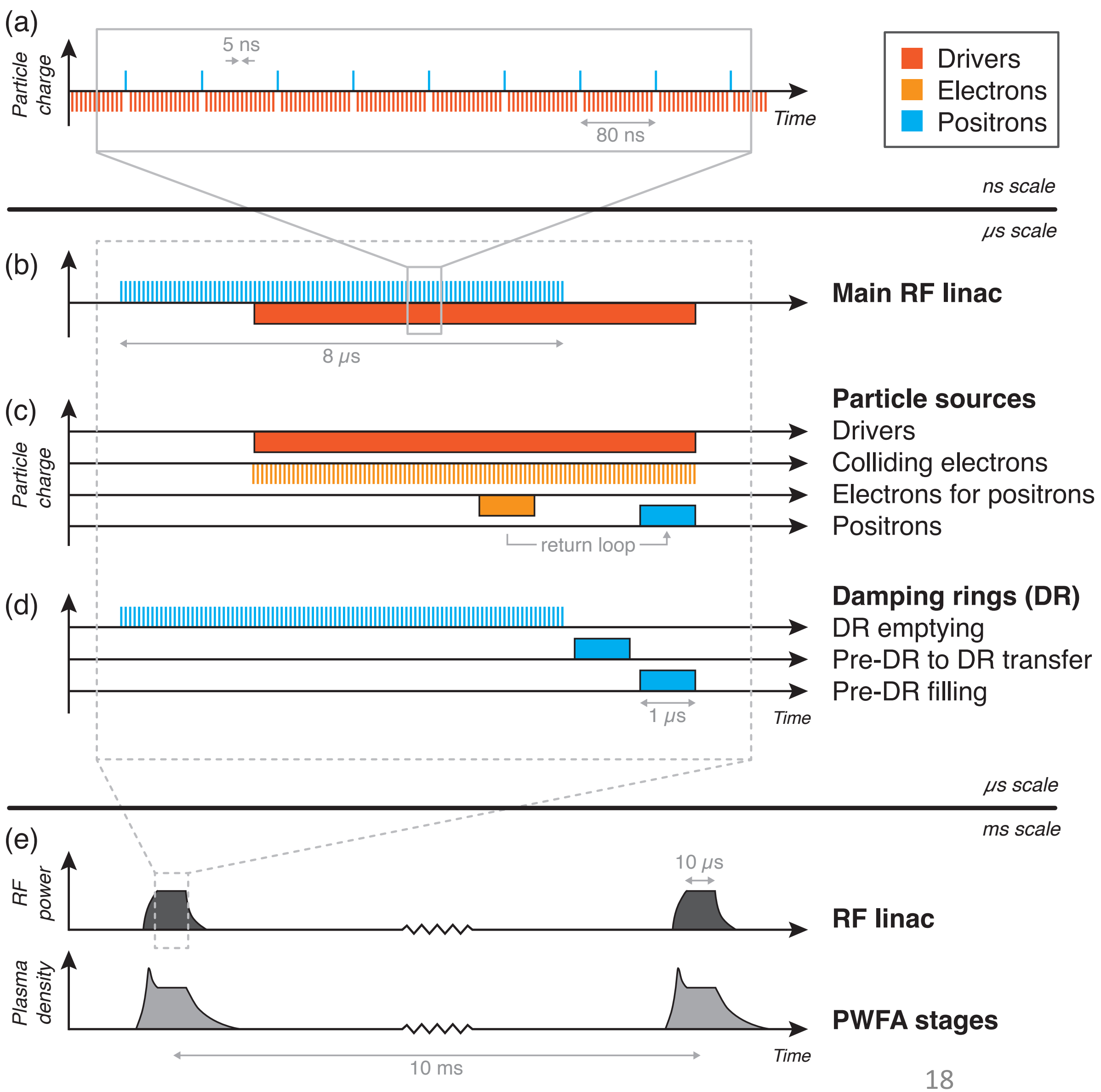
- Drivers go through turn-around and then distributed to plasma cells via undulating delay chicane.
- Assuming TR ~ 1, e- bunch accelerated by 31 GeV/5m stage => 16 stages with $\rho \sim 7*10^{15}$ => 6.4 GV/m.
- Interstage optics needs ~ <26.5m> but scales with sqrt(E).
- Total length of PWFA linac = 410m.



Bunch-train pattern.



- Assuming L-band linac:



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).

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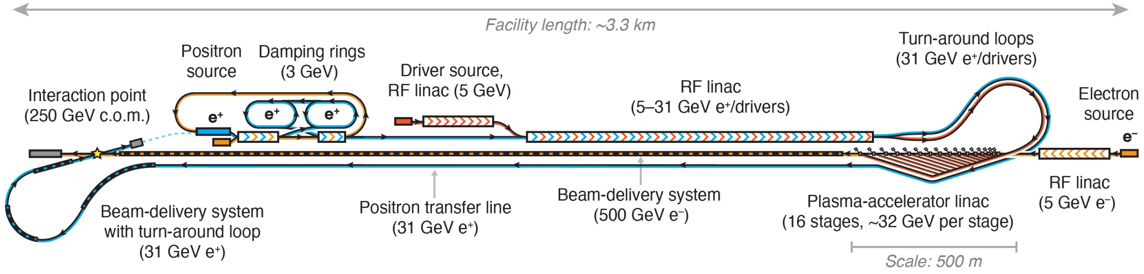
Cost Estimate

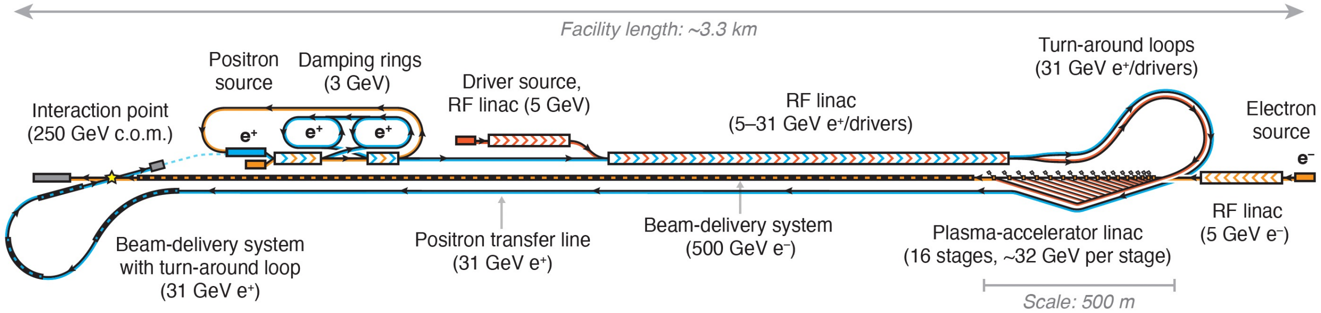


- Scale from existing costed projects wherever possible – mostly ILC – very rough – not better than 25% accurate.

Subsystem	Original cost (MILCU)	Comment	Scaling factor	HALHF cost (MILCU)	Fraction
Particle sources, damping rings	430	CLIC cost [69], 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 [47], 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%

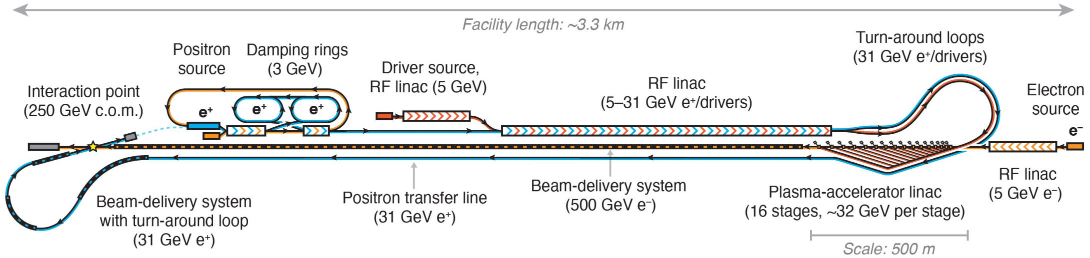
[a] Swiss deflator from 2018 → 2012 is approximately 1. Conversion uses Jan 1st 2012 CHF to $ exchange rate of 0.978.
[b] Cost of PWFA linac similar to ILC standard instrumented beam lines plus short plasma cells & gas systems plus kickers/chicanes. The factor 6 is a rough estimate of extra complexity involved.
[c] The positron transfer line, which is the full length of the electron BDS, dominates; this plus two turn-arounds, the electron transport to the positron source plus small additional beam lines are costed.
[d] The HALHF length is scaled by $\sqrt{E}$ and the cost assumed to scale with this length.
[e] Length of excavation and beam line taken from European XFEL dump.

Cost Estimate



- Snowmass study ITF of various accelerator costs gives ILC Higgs Factory Total Project Cost (TPC) (= US accounting) of $7 – 12B (2021 $). Scaling this by the value estimate (~European accounting) of HALHF/ILC@Snowmass gives HAHLF TPC ~ $2.3 – 3.9B: c.f. EIC TPC = ~< $2.8B. Direct estimate by ITF people (Seeman/Gessner) gives $4.46B.

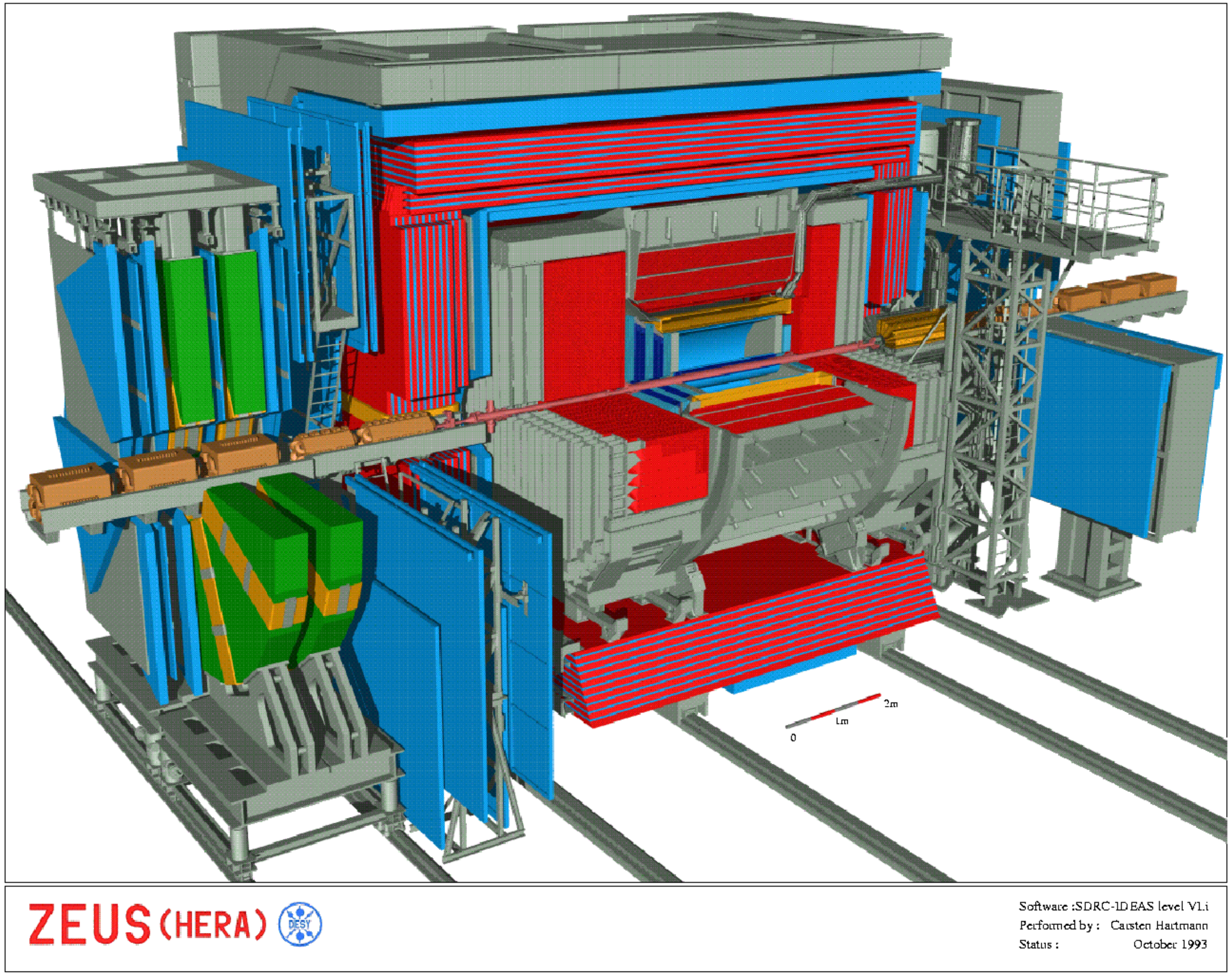
Running Costs



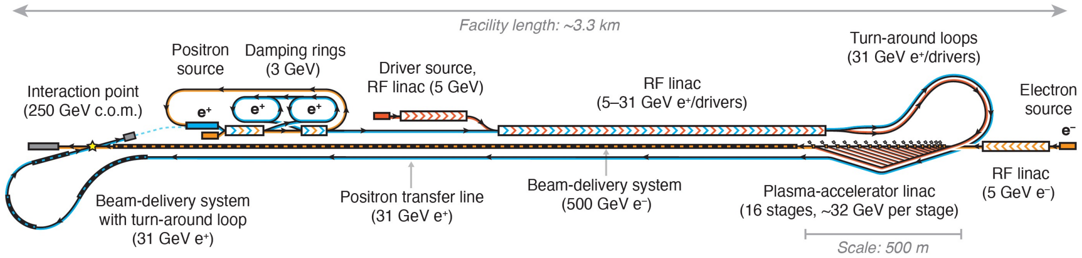
- Dominated by power to produce drive beams.
- (100*16*4.3nC + 6.4nC)*100 => 47.5 MW@50% eff.
- Damping rings: 2*10 MW.
- Cooling – assume similar to CLIC => 50% of RF power (corresponds to 20 kW/m).
- For magnets and other conventional sources assume ~9 MW.
- Gives total power requirement ~ 100 MW – similar to other proposals.

Experimentation at HALHF

- Boost is smaller than HERA - HERA detectors very similar to those at symmetric machines.
- Preliminary study (M. Berggren) with long ILD barrel shows ~ similar Higgs resolution.
- Measurement of $\mathcal{L}$ via Bhabha (e^+e^- -> e^+e^-) - rate reduced by $1/(\theta\gamma)^2$ & e^+ scattered into barrel – but not a problem. Singles rate good for machine optimisation

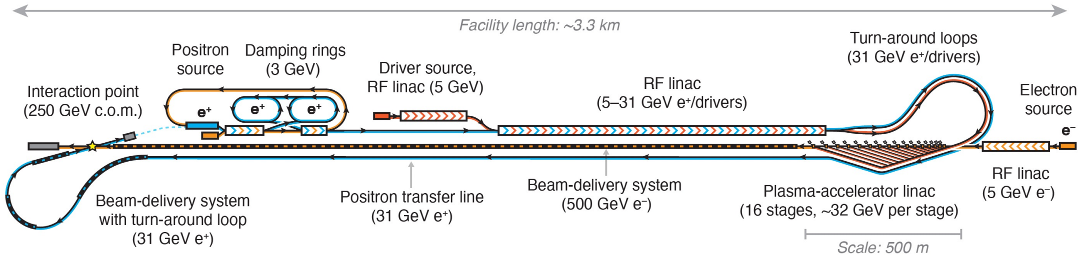


Summary & Outlook



- HALHF benefits from maximal asymmetry.

Summary & Outlook



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- Even if e^+ acceleration not a problem, HALHF could still be best way forward – but requires > a decade of significant R&D.

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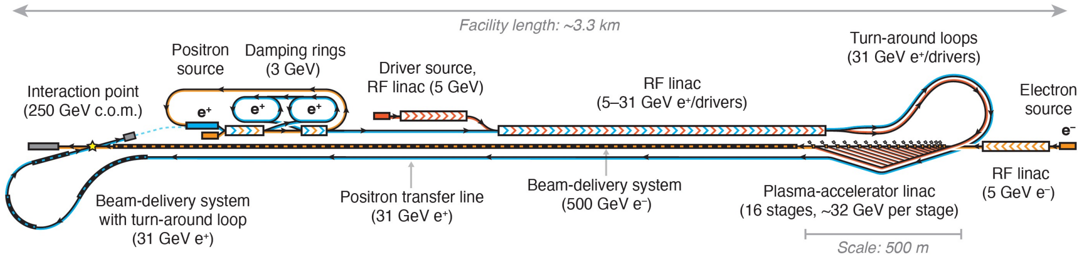

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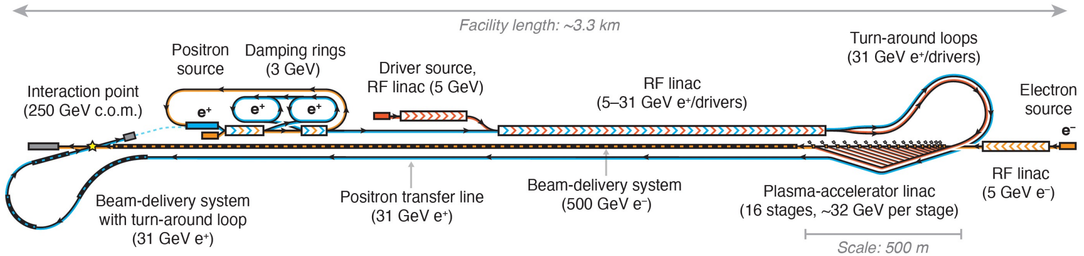

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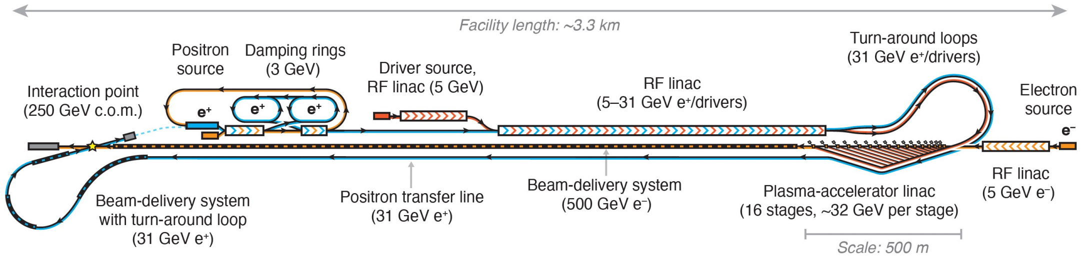

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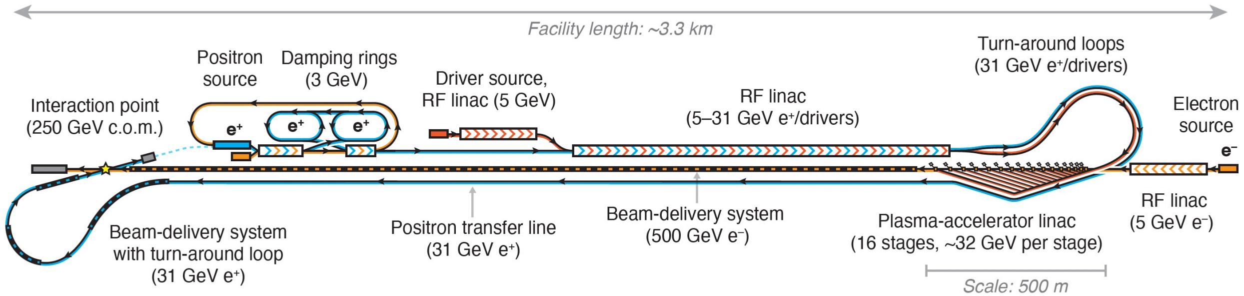
- Conventional design work needed: DR with high bunch charge; heavily loaded linac; BDS…
- PWFA R&D: higher accelerated charge (x ~10), higher repetition rate (x ~1000), plasma-cell power dissipation (x ~1000), beam jitter reduction (x ~10-100).
- Better start asap – HALHF “kick-off” meeting @ DESY on 23.10.23

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

Project Staging



- Any project of this size and scope needs a ~10% prototype. A few cells producing useful currents of e^- at few 100 GeV would be very interesting for SFQED.
- Once satisfactory performance demonstrated, remaining elements can be constructed and then running at Z can be used to tune up machine and detector.

Upgrades

- Energy upgrade: keep e^+ energy same increases γ as E increases – experiments more and more difficult; increasing e^+ energy to keep γ ~ constant gives expensive linac.
- However, getting to ttbar threshold with same e^+ energy => E(e-) ~ 1 TeV and γ ~ 2.9, still less than at HERA and ttbar final state even more spherical. Keeping γ constant by lengthening conventional linac needs $E(e^+)$ ~ 44 GeV and $E(e^-)$ ~ 700 GeV. (space allocated and tunnel already built both for linac &BDS).
- Produce e^+ polarization via ILC-like scheme - ideas exist for $E(e^-)$ 500 GeV.