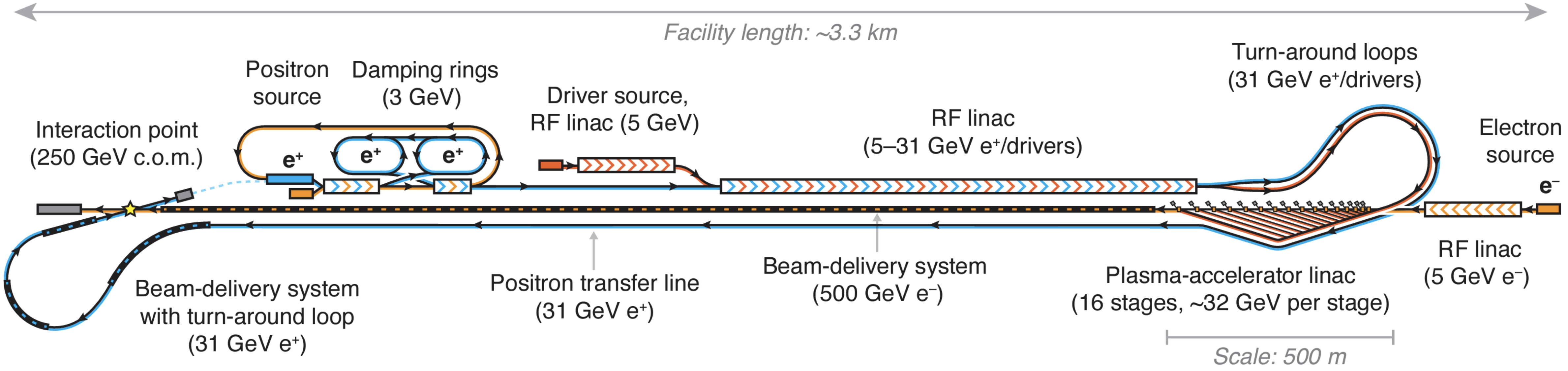
HALHF: A Hybrid Asymmetric Linear Higgs Factory



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On behalf of Brian Foster and Carl Lindstrøm

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

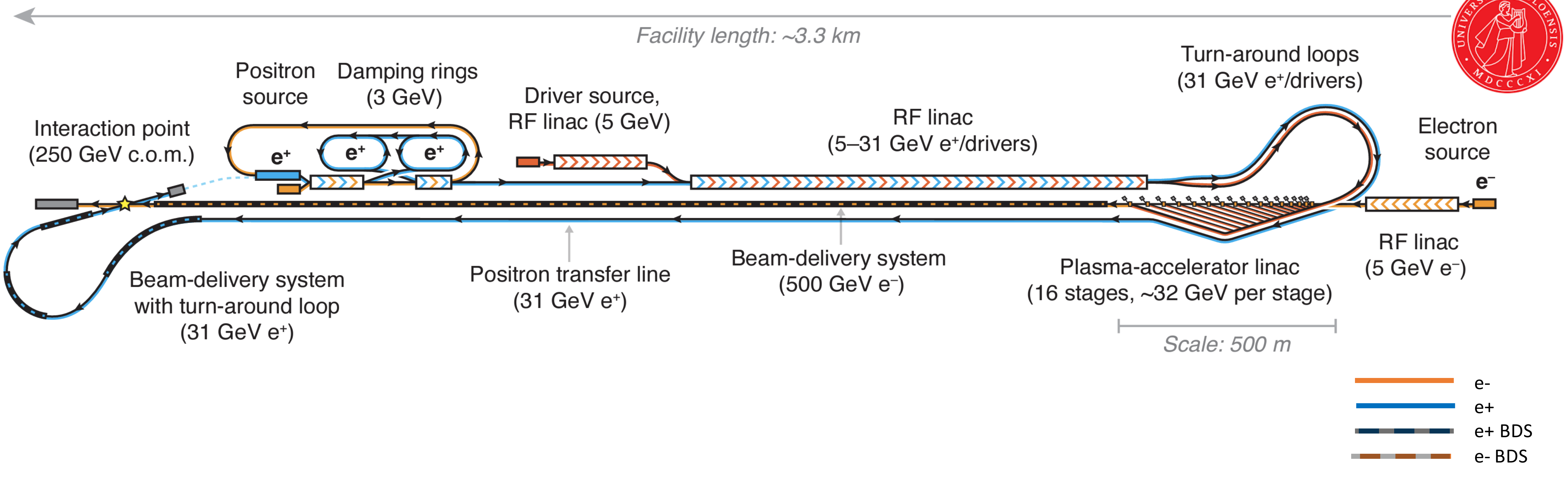
$$E_e + E_p = \gamma\sqrt{s}, \quad (2)$$

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 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. There is a service tunnel a la ILC (not shown))

HALHF Parameter Table

Machine parameters	*Unit*		
Center-of-mass energy	GeV	250	
Center-of-mass boost		2.13	
Bunches per train		100	
Train repetition rate	Hz	100	
Collision rate	kHz	10	
Luminosity	$cm^{-2}\,s^{-1}$	0.81×10^{34}	
Peak luminosity (in top 1%)		57%	
Estimated total power usage	MW	100	
Beam parameters		e^-	e^+
Beam energy	GeV	500	31.25
Bunch population	10^{10}	1	4
Bunch length in linac (rms)	μm	9	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
Average beam current	mA	0.016	0.064

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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 parameters		
Number of stages		16
Plasma density	cm^{-3}	1.5×10^{16}
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	27.6
Driver average beam power	MW	21.4
Driver-to-wake efficiency	%	74
Wake-to-beam efficiency	%	53
Driver-to-beam efficiency	%	39
Wall-plug-to-beam efficiency	%	19.5
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).

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 => 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 β_x / β_y = 3.3/0.1 mm c.f. CLIC 4.0/0.1 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 L => increased tolerances in PWFA arm.
- Beam-beam focusing effect on L must be simulated with Guinea Pig.

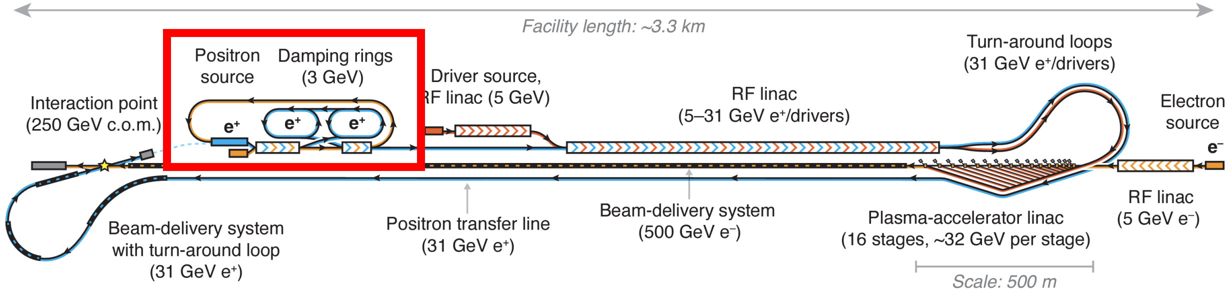
Luminosity estimation

- 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	1.58	1.18	1
31.3 / 500	300 / 300	2 / 2	10 / 10	35 / 35	3.3 / 52	0.10 / 1.6	1.32	0.92	2.13
31.3 / 500	75 / 75	2 / 2	10 / 10	35 / 35	3.3 / 52	0.10 / 1.6	1.52	0.96	2.13
31.3 / 500	75 / 75	4 / 1	10 / 10	35 / 35	3.3 / 52	0.10 / 1.6	1.45	0.78	1.25
31.3 / 500	75 / 75	4 / 1	10 / 40	35 / 140	3.3 / 13	0.10 / 0.41	1.42	0.76	1.25
31.3 / 500	75 / 75	4 / 1	10 / 80	35 / 280	3.3 / 6.5	0.10 / 0.20	1.35	0.71	1.25
31.3 / 500	75 / 75	4 / 1	10 / 160	35 / 560	3.3 / 3.3	0.10 / 0.10	1.16	0.60	1.25

- ILC
- HALHF
- HALHF with reduced emittance for PWFA

Positron Source



- "Conventional" e^+ sources are not trivial – that for ILC, which has relaxed requirements wrt HALHF, 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.

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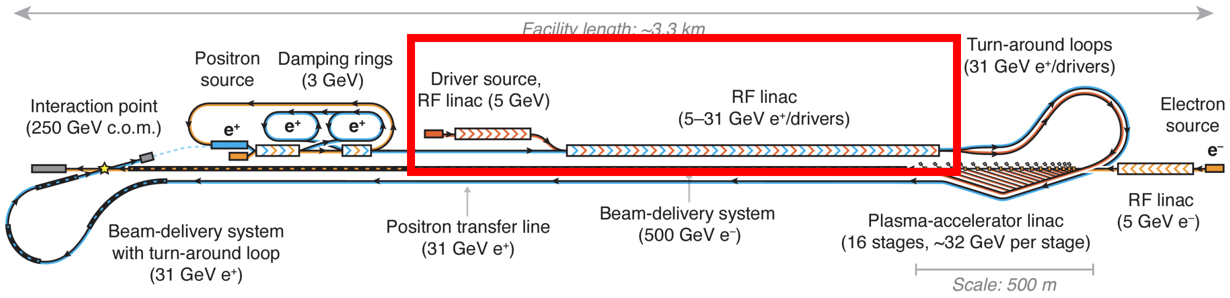
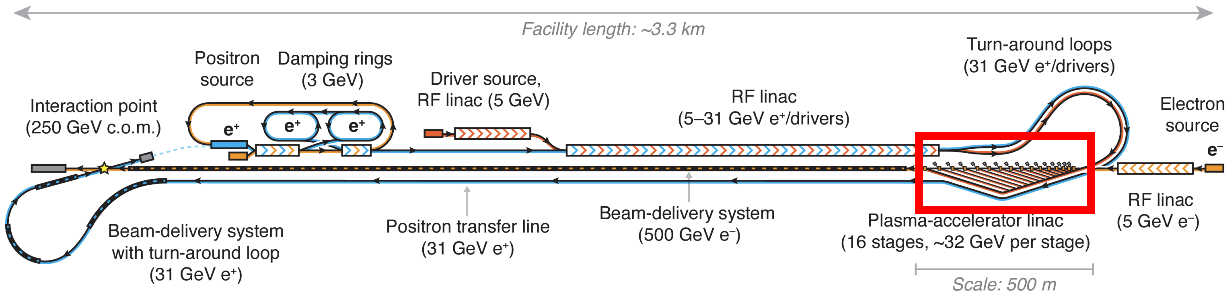
Main RF Linac

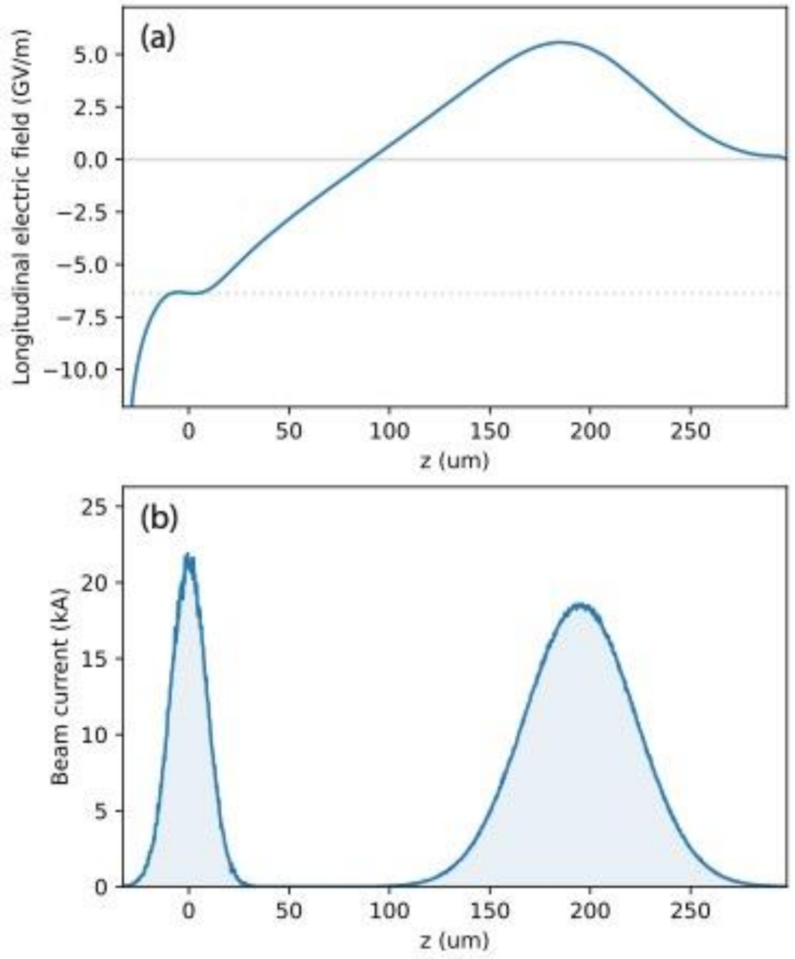


- Split in two parts: accelerate e^- PWFA drive beams from 1 ➞ 5 GeV; then both e^+ and e^- from 5 ➞ 31.3 GeV.
- Assume acc. gradient of 25 MV/m ➞ 1.25 km long.
- Assume warm L-band linac – if necessary CW SRF could be used but would increase cost and change bunch pattern.
- Before drivers, e^+ bunch accelerated with 180° phase offset.

PWFA Linac



- Drivers go through turn-around loops and are then distributed to plasma cells via an undulating delay chicane
- Assuming TR ~ 1, e- bunch accelerated by 31 GeV/5m stage ➞ 16 stages with ρ ~ $1.5*10^{16}$ cm^{-3} ➞ 6.2 GV/m.
- Interstage optics needs ~ <26.5m> but scales with sqrt(E).
- Total length of PWFA linac = 410m.



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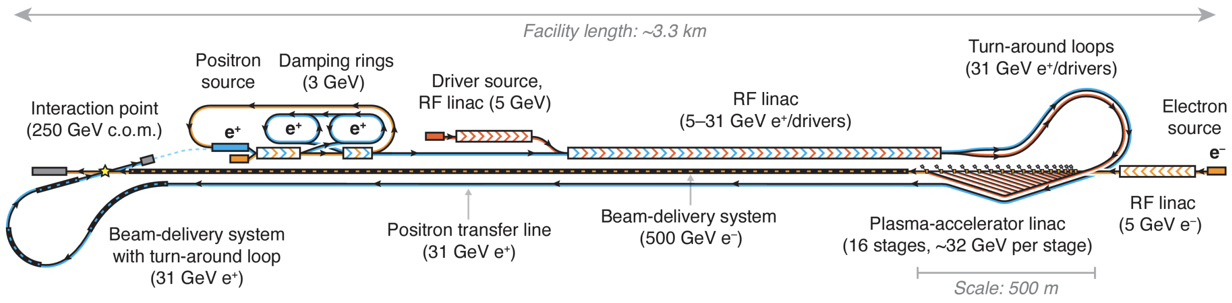
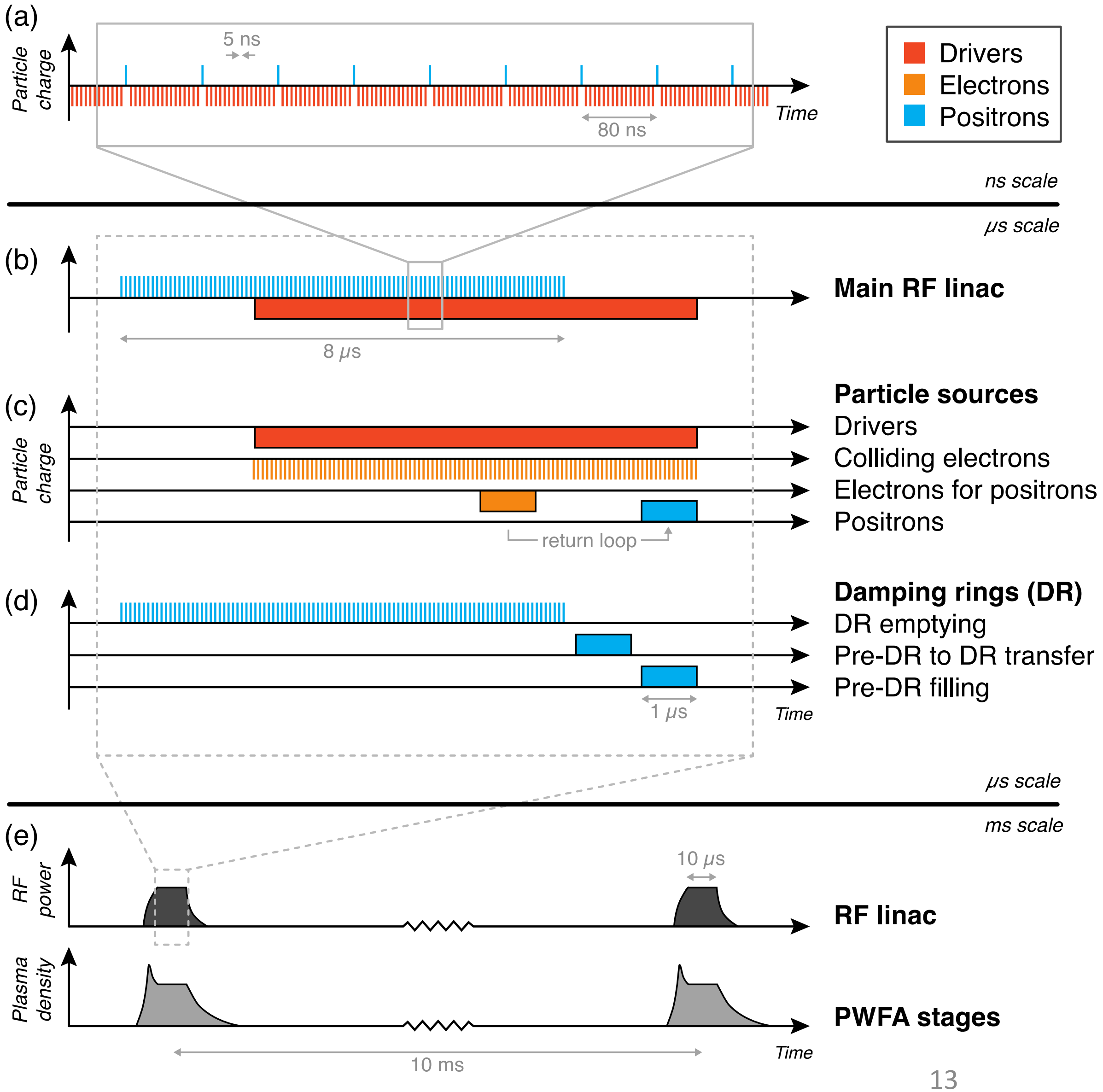
Bunch-train pattern.



- Assuming L-band linac:
  - 80 ns colliding-bunch separation
  - 125 colliding bunches / 10 µs train
  - 100 trains / s
  - 12500 collisions / s



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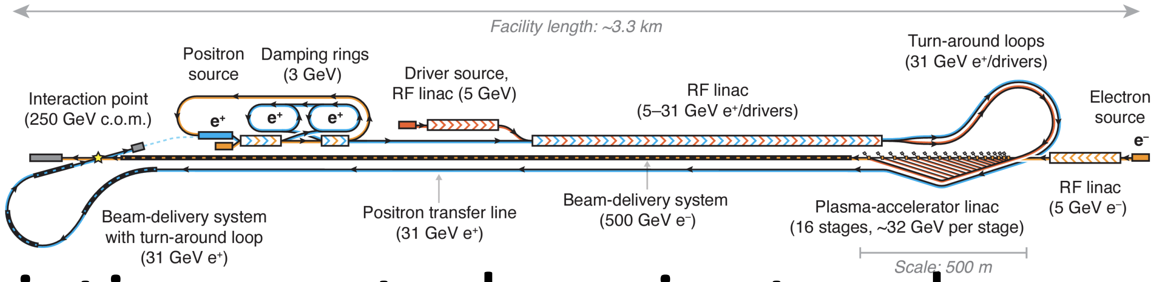
Cost Estimate

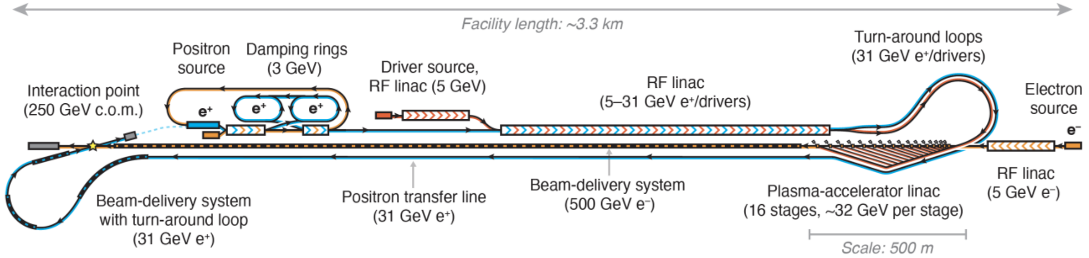


- Scale from existing costed projects wherever possible – mostly ILC – very rough – not better than 25% accurate.

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.

Running Costs



- Dominated by power to produce drive beams.
  - (100*16*4.3nC + 6.4nC)*100 ➞ 47.5 MW@50% efficiency
- 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 – somewhat smaller than other proposals.

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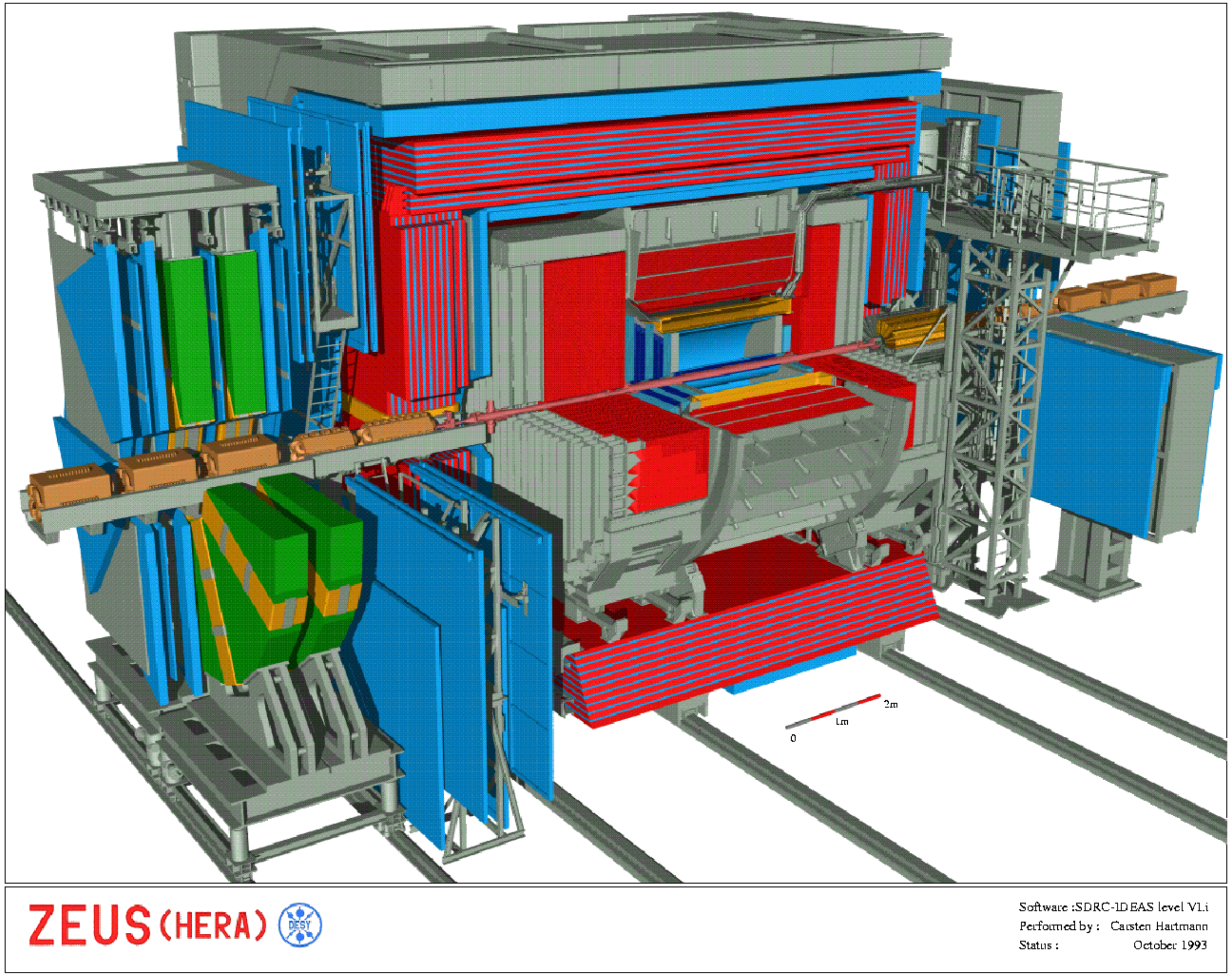
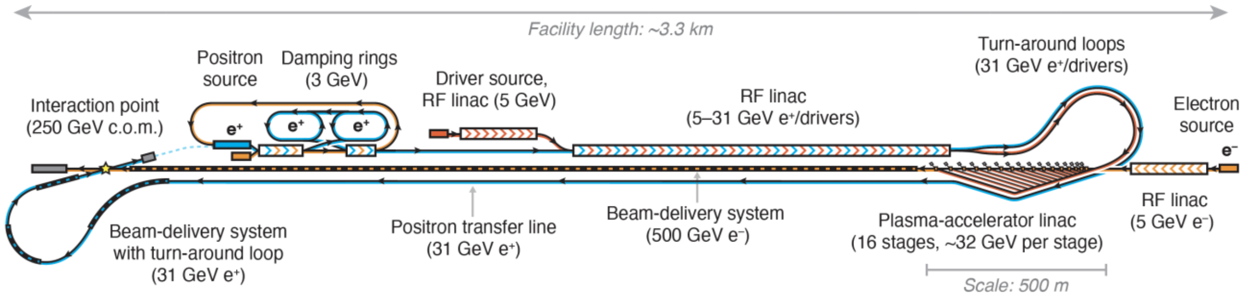
Experimentation at HALHF

- Boost is smaller than HERA - HERA detectors very similar to those at symmetric machines.
- Also H & Z heavy, so anyway more homogeneous.
- Measurement of L via Bhabha ($e^+e^- \rightarrow e^+e^-$) - rate reduced by $1/(\theta\gamma)^2$ & e^+ scattered into barrel – but not a problem. Singles rate good for machine optimisation



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.

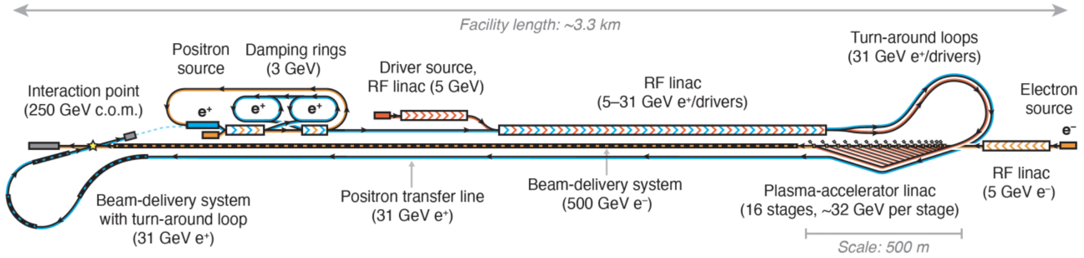
Upgrades (1)

- HALHF not competitive in L with circular machines at Z and gets more expensive and complicated at high E. 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.
- Alternatively, keeping γ constant by lengthening conventional linac (space allocated and tunnel built already in anticipation) needs $E(e^+)$ ~ 44 GeV and $E(e^-)$ ~ 700 GeV.

Upgrades (2)

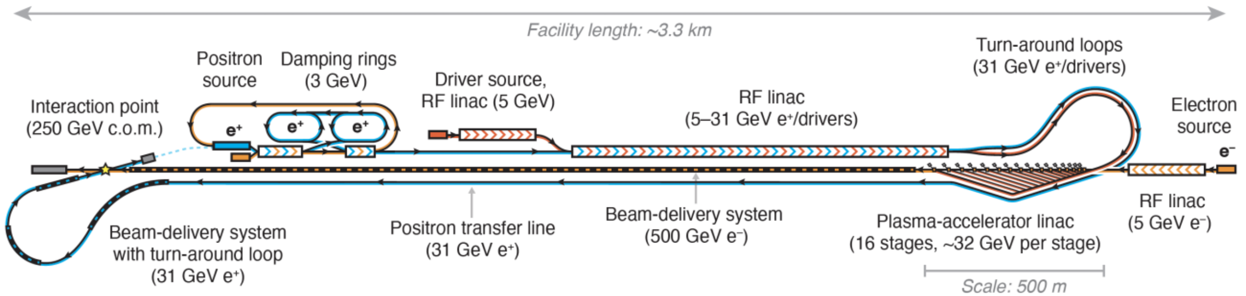
- $\gamma - \gamma$ collider also avoids e^+ PWFA acceleration. Switch out e^+ source and construct another PWFA linac.
- Produce e^+ polarization via ILC-like scheme. Would require bypass in PWFA linac at ~ 250 GeV into wiggler and rotating target – but wiggler very long to get ~ 15% e+ polarization. Important for physics but halves L (unless linac more heavily loaded).

Summary & Conclusion



- HALHF benefits from maximal asymmetry.
- Even if e^+ acceleration not a problem, HALHF could still be best way forward – but requires significant R&D.
- Conventional design work needed: DR with high bunch charge; heavily loaded linac; BDS…
- PWFA R&D: long hot cells & cooling; high-charge beams; high rep. rate; staging of plasma sources; jitter…
- Several (!) years of work required.

Summary & Conclusion



- BUT – if R&D successful, HALHF is the first e+e- Higgs Factory proposal that costs ~ same as projects that can be built inside a national programme (cf XFEL, EIC, etc.)
- Success would be major achievement for both PWFA and particle physics
- For accelerator physicists – don't be afraid of the plasma; for particle physicists – don't be afraid of the boost; for plasma-wakefield community – come up with the goods!