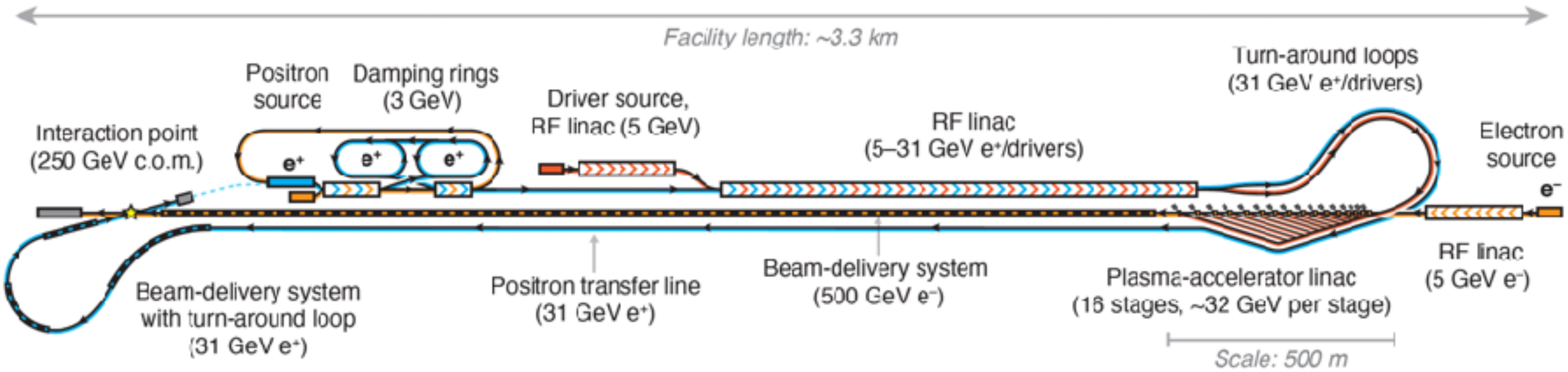
Hybrid Asymmetric Linear Higgs Factory (HALHF)

B. Foster, R. D’Arcy & C.A. Lindstrøm



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

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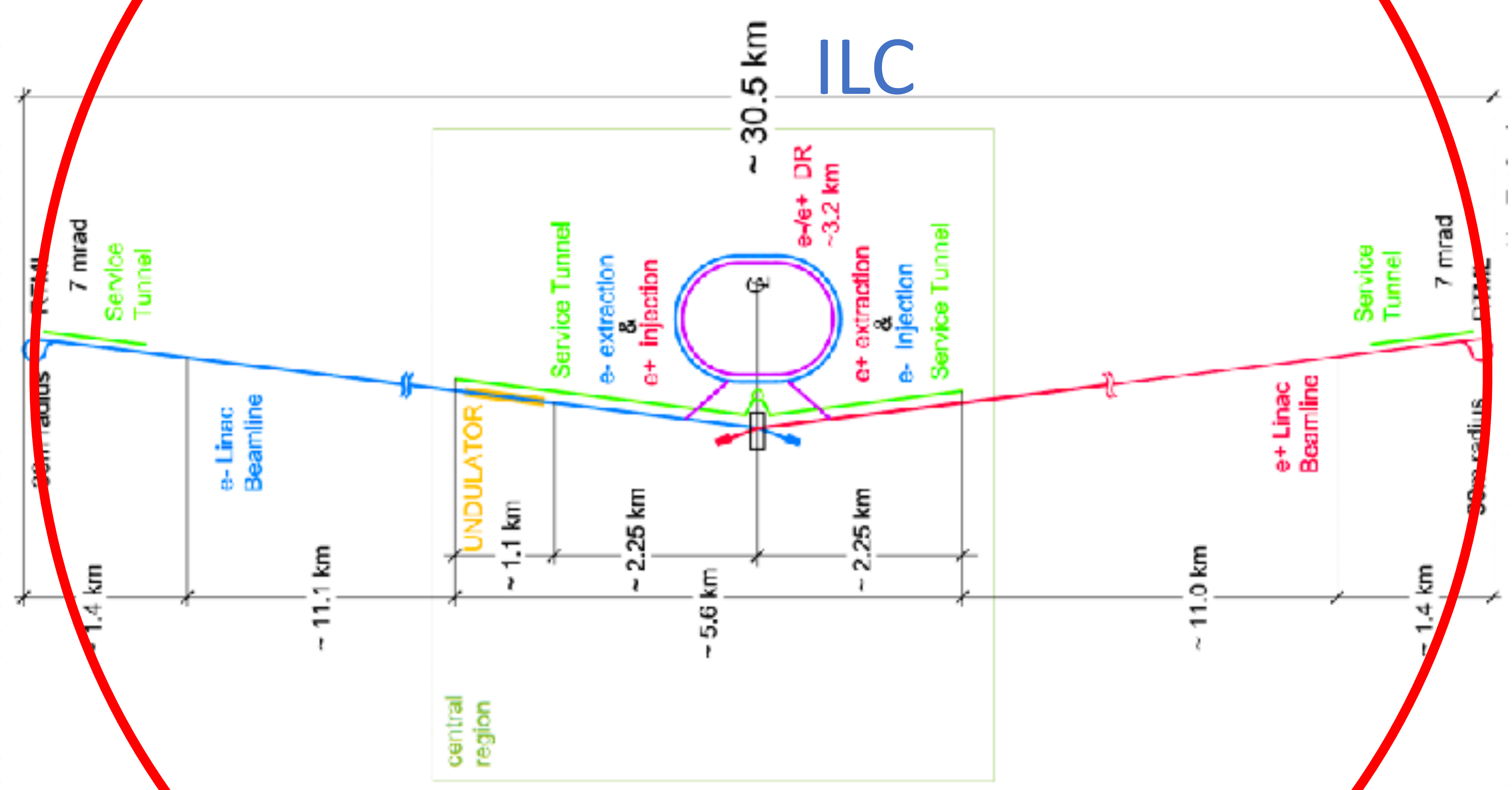
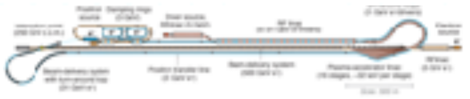
ILC

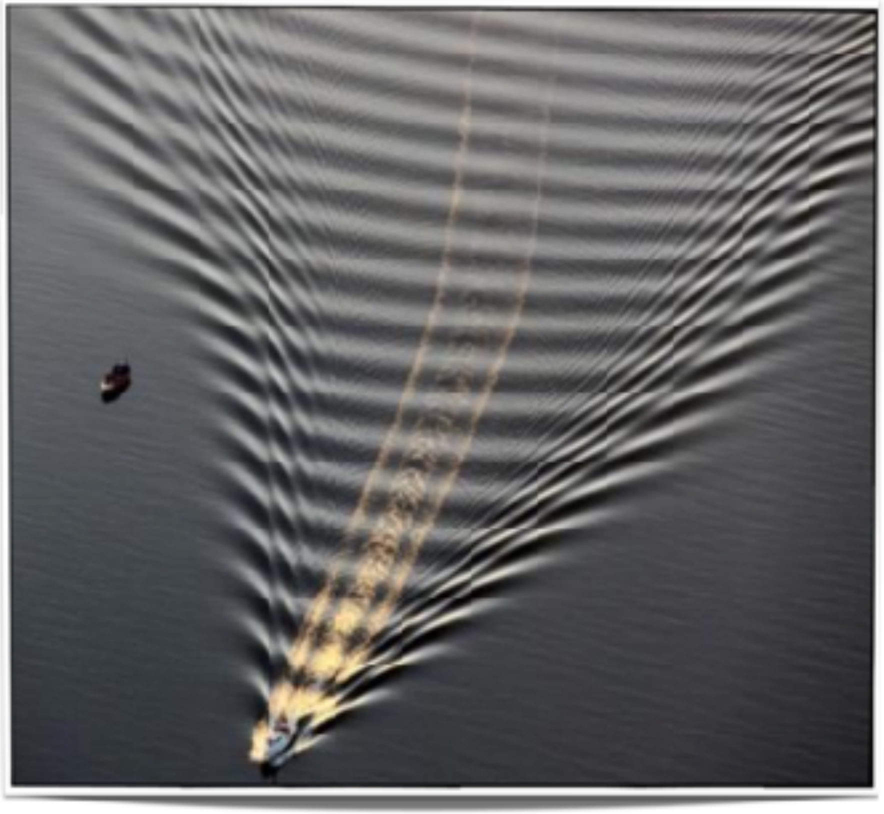


FCC



https://arxiv.org/2303.10150

Plasma Wave Acceleration

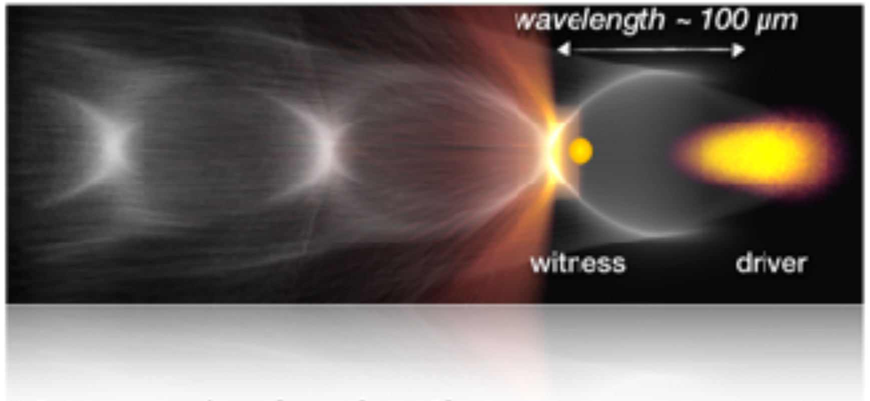


Wake Excitation

Particle Acceleration

Plasma Wave Acceleration

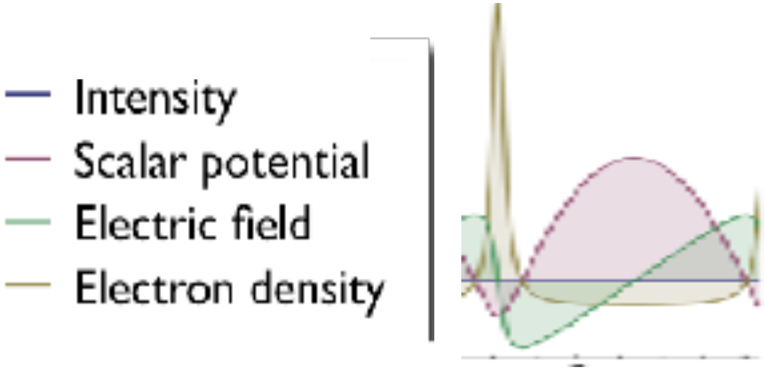
Charge density wave in a plasma

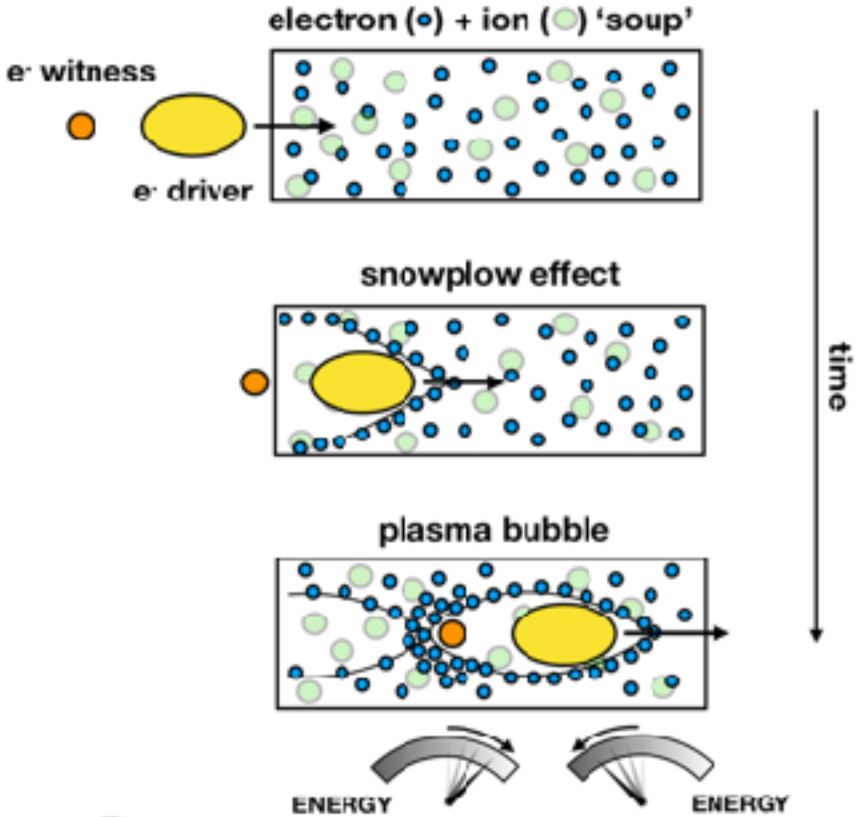


Femtosecond pulse duration

Intrinsically short due to short plasma wavelength

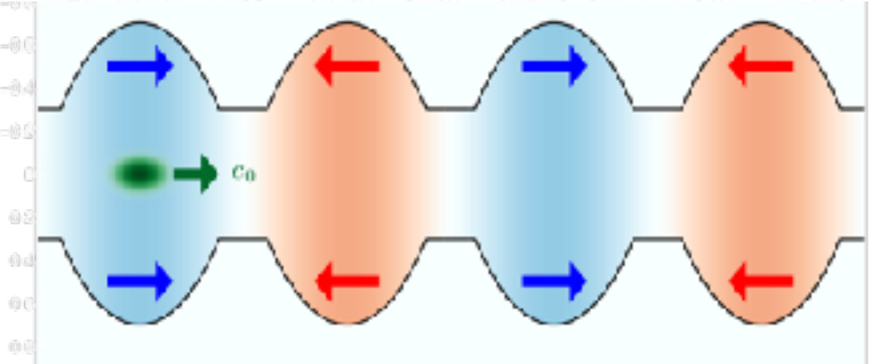
GV/m acceleration gradients



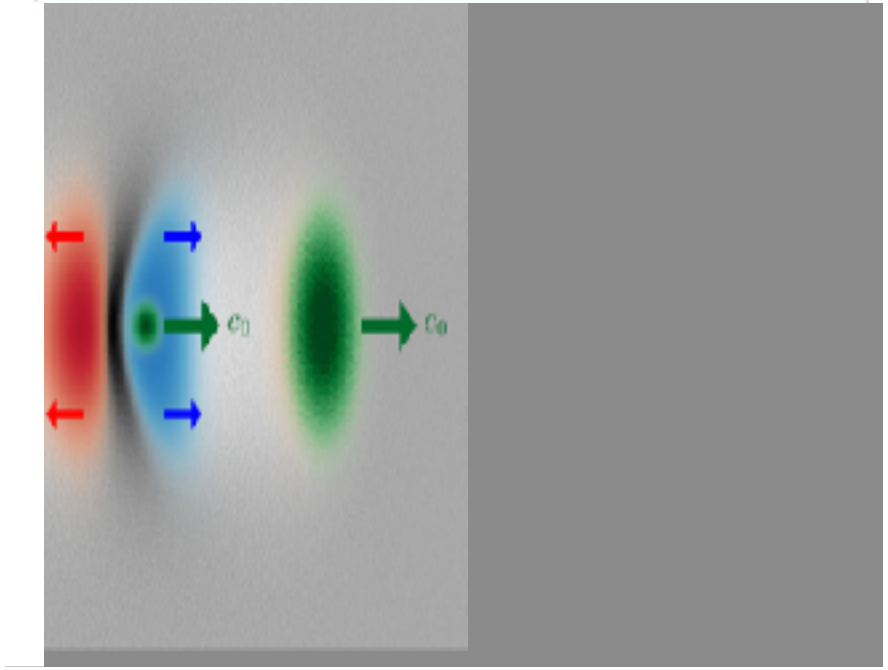


Cavities cf Plasmas

SCRF Cavity

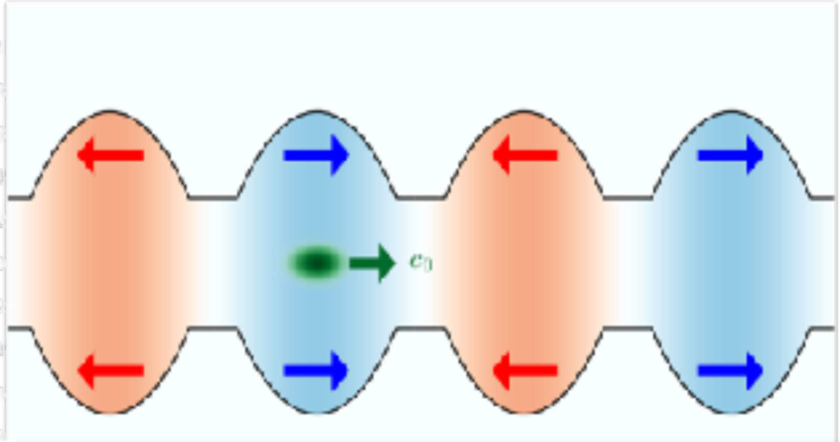


Plasma wakefield

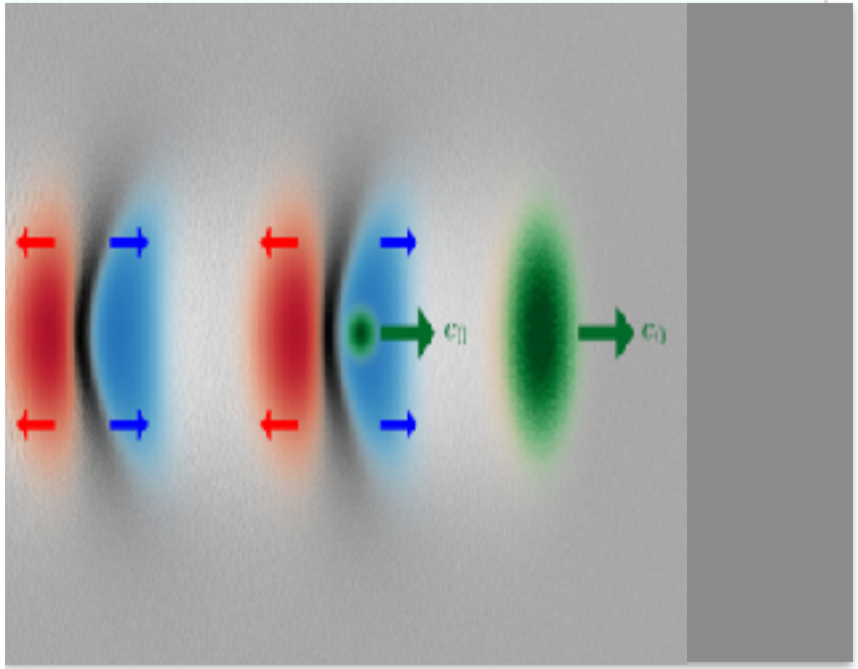


Cavities cf Plasmas

SCRF Cavity



Plasma wakefield



Setting the scale

Plasma frequency depends only on density

$$\omega_p^2 = \frac{4\pi n_p e^2}{m}$$

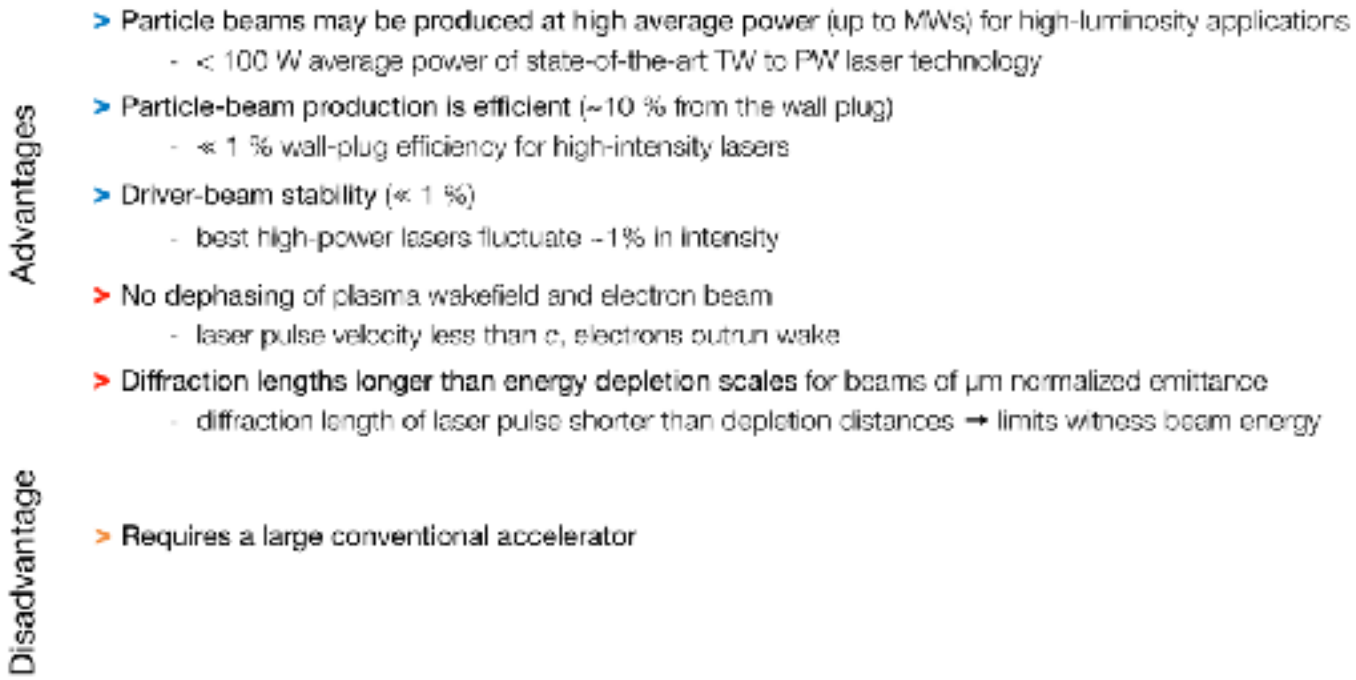
$$k_p = \frac{\omega_p}{c}$$

$$\lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1 \cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

LWFA & PWFA

- Two main methods of exciting a wake-field in a plasma
  a) Using a high-powered laser (LWFA)
  b) Using electric field from intense particle beam (PWFA)

- Each has advantages & disadvantages – for PWFA:



Advantages

> Particle beams may be produced at high average power (up to MWs) for high-luminosity applications
  - < 100 W average power of state-of-the-art TW to PW laser technology

> Particle-beam production is efficient (~10 % from the wall plug)
  - ≪ 1 % wall-plug efficiency for high-intensity lasers

> Driver-beam stability (≪ 1 %)
  - best high-power lasers fluctuate ~1% in intensity

> No dephasing of plasma wakefield and electron beam
  - laser pulse velocity less than c, electrons outrun wake

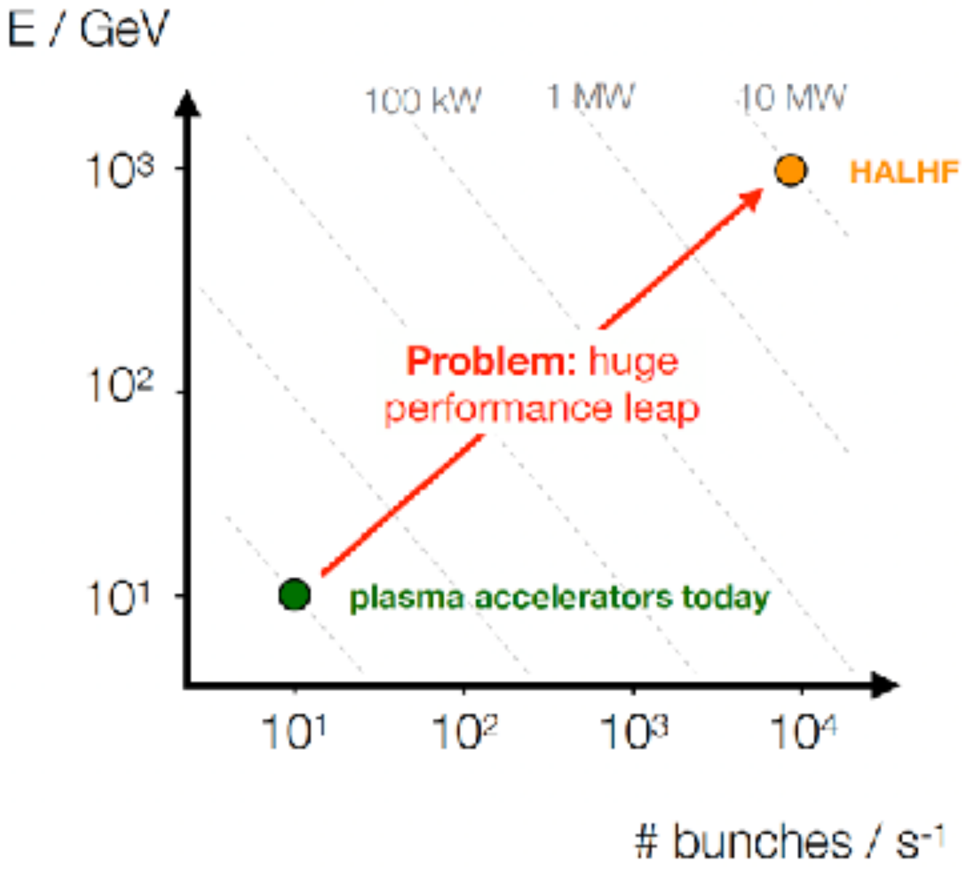
> Diffraction lengths longer than energy depletion scales for beams of μm normalized emittance
  - diffraction length of laser pulse shorter than depletion distances → limits witness beam energy

Disadvantage

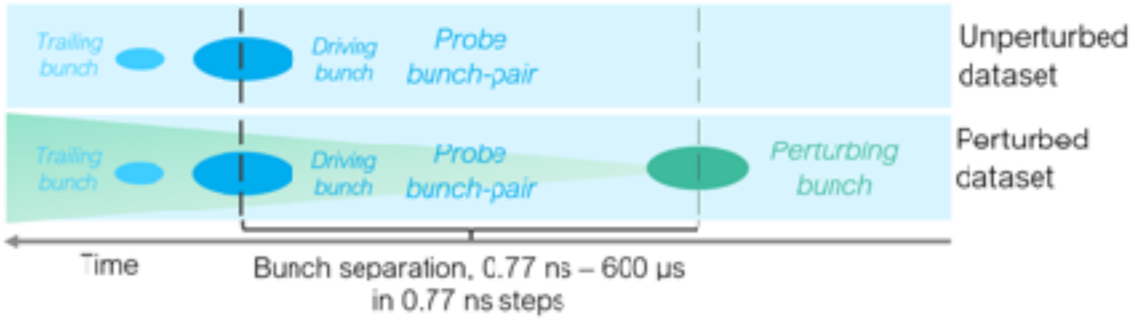
> Requires a large conventional accelerator

Long Journey Ahead

FLASHForward@DESY results



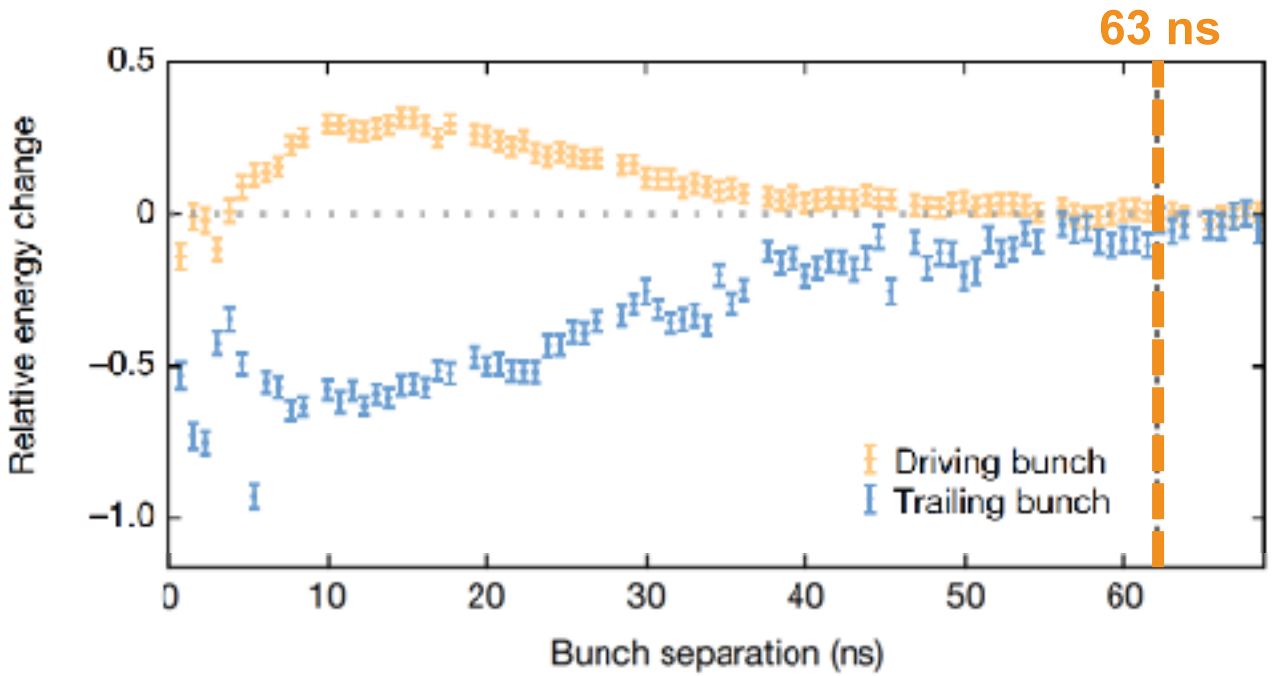
Rate limits in Plasma

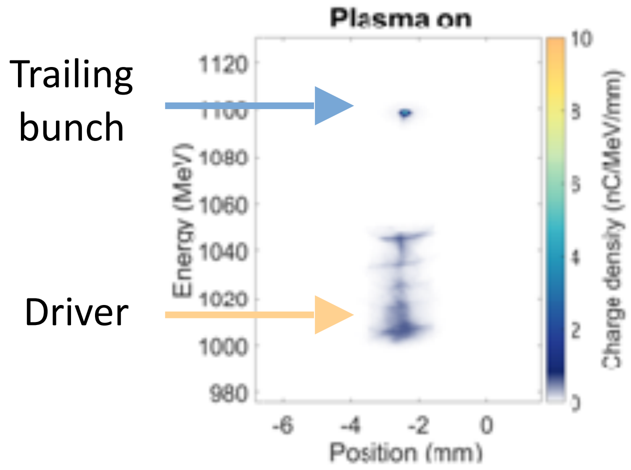


Demonstrates >10 MHz repetition

Rate in Ar – lighter gases faster.

[1]





Accelerated bunch on the energy spectrometer

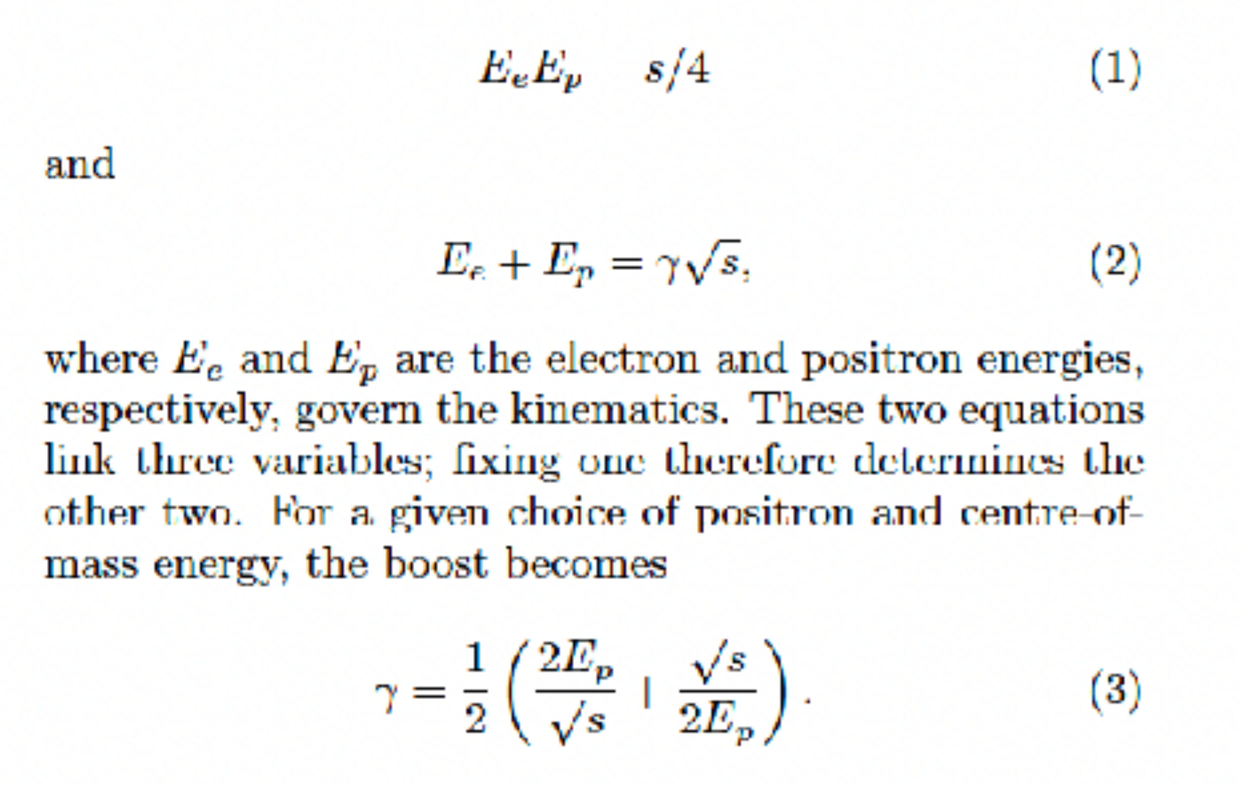
Diagram and image courtesy: F. Pena, J. Beinortaitė

[1] R. D'Arcy, BF, et al., Nature **603**, 58-62 (2022)

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



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

and

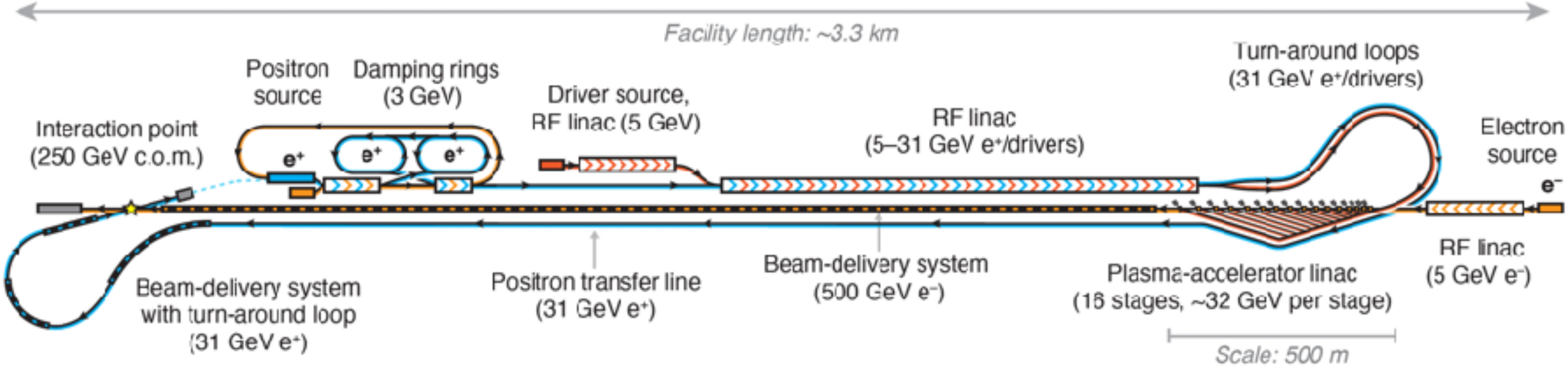
$$E_e + E_p = \gamma\sqrt{s}, \qquad (2)$$

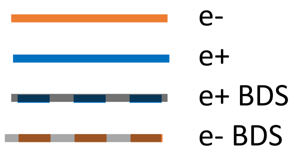
where E_e and E_p are the electron and positron energies, respectively, govern the kinematics. These two equations link three variables; fixing one therefore determines the other two. For a given choice of positron and centre-of-mass energy, the boost becomes

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

- 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.

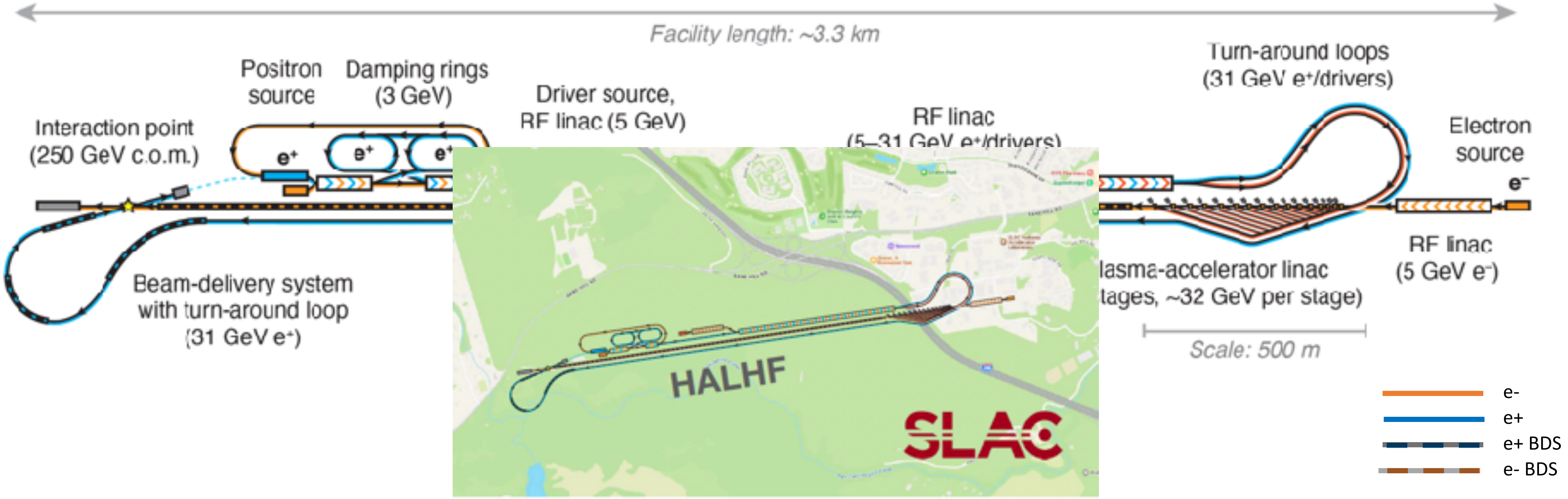
HALHF Layout





- 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)

HALHF Layout



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

Energy Efficiency

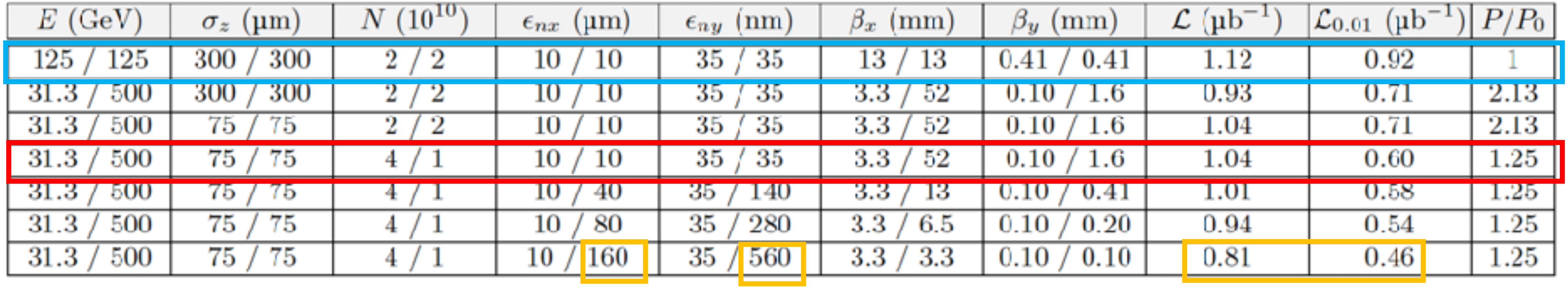
- Asymmetric machines less energy efficient than symmetric – energy lost "in accelerating the C.o.M." For equal bunch charges => 2.5 times more energy required for same C.o.M. energy.
- Can be reduced by introducing asymmetry into beam charges – increase charge of low-energy beam and decrease high-energy 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 8.0/0.1 mm.
- In contrast, high-energy e^- beam - β function can be increased.
- 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.

Beam-beam Effects

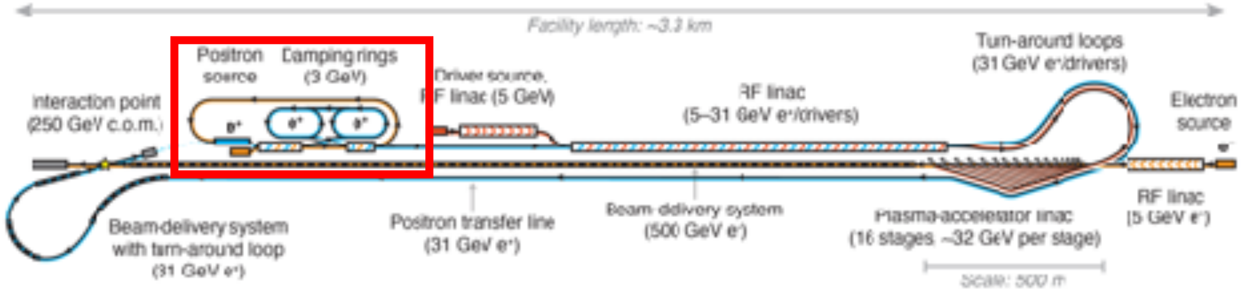
- Guinea-Pig results:



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

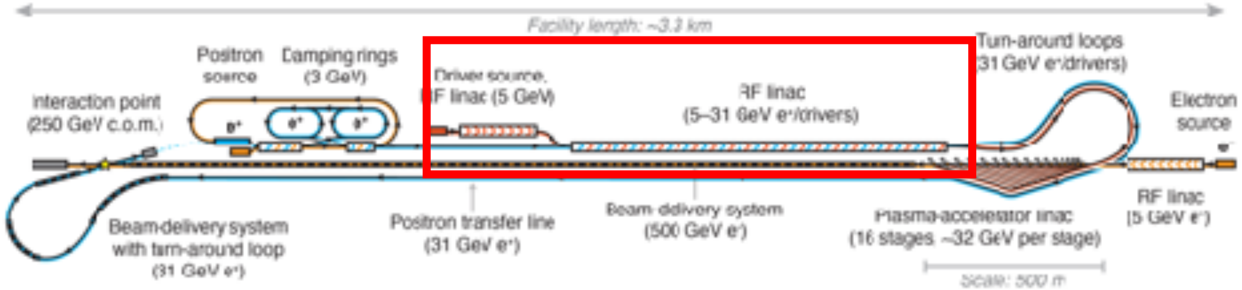
- ILC
- HALHF
- HALHF with reduced emittance for PWFA

Positron Source



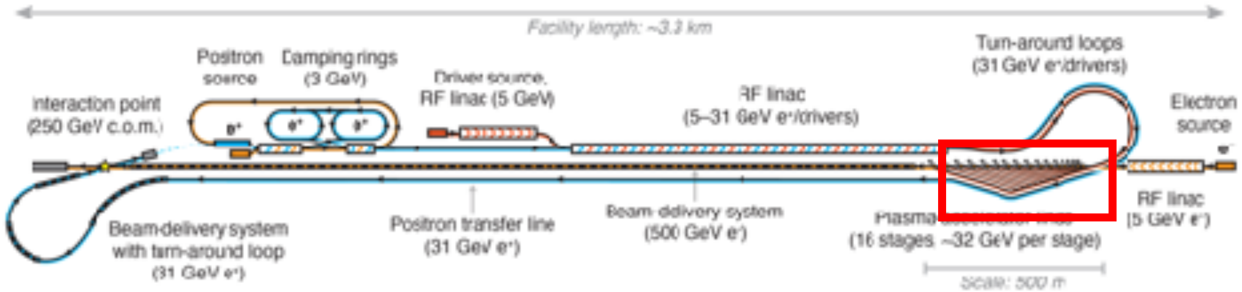
- “Conventional” e^+ sources are not trivial – that for ILC, which has relaxed requirements wrt HAHLF, still under development.
- e^- accelerated to 5 GeV and then collide with target to produce e^+ which are accumulated, bunched and accelerated to 3 GeV and then damped in 2 rings (~identical to CLIC 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

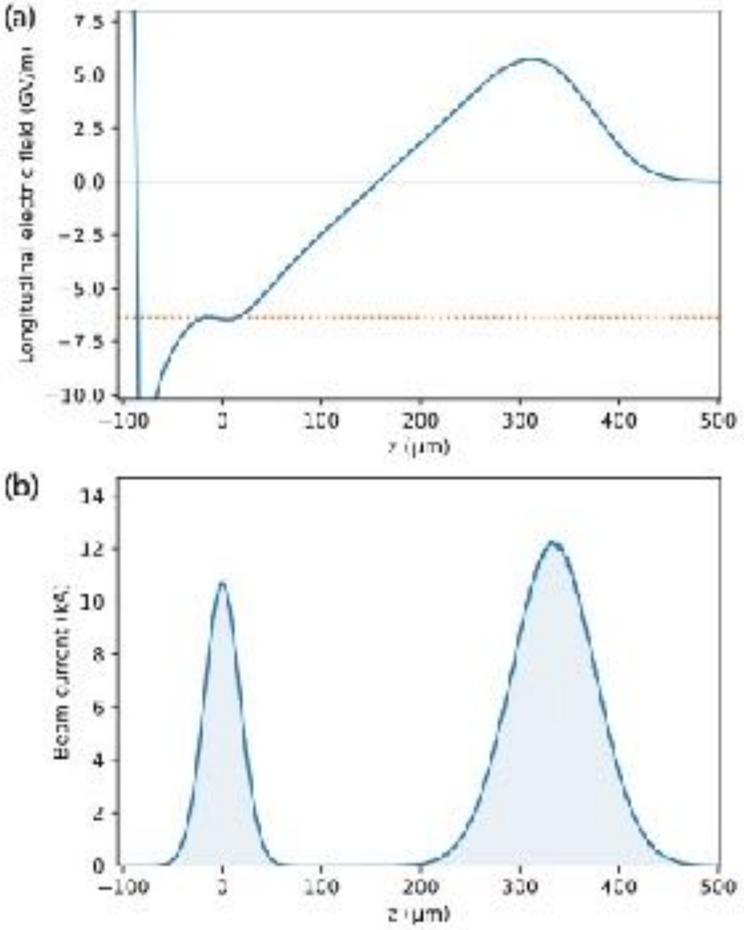


- Split in 2, to accelerate e^- PWFA drive beams from 1 – 5 GeV & then both e^+ and e^- from 5 GeV to 31.3 GeV.
- Assume gradient of 25 MV => 1.25 km long.
- Delivers total average power of 21.4 MW => including e^+ power and $\varepsilon \sim 50\%$, wall-plug 47 MW.
- Assume warm L-band linac – CW SRF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

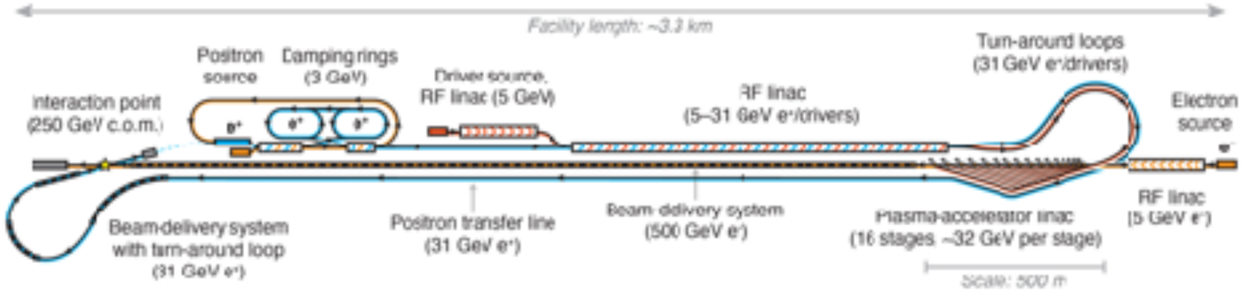
PWFA Linac



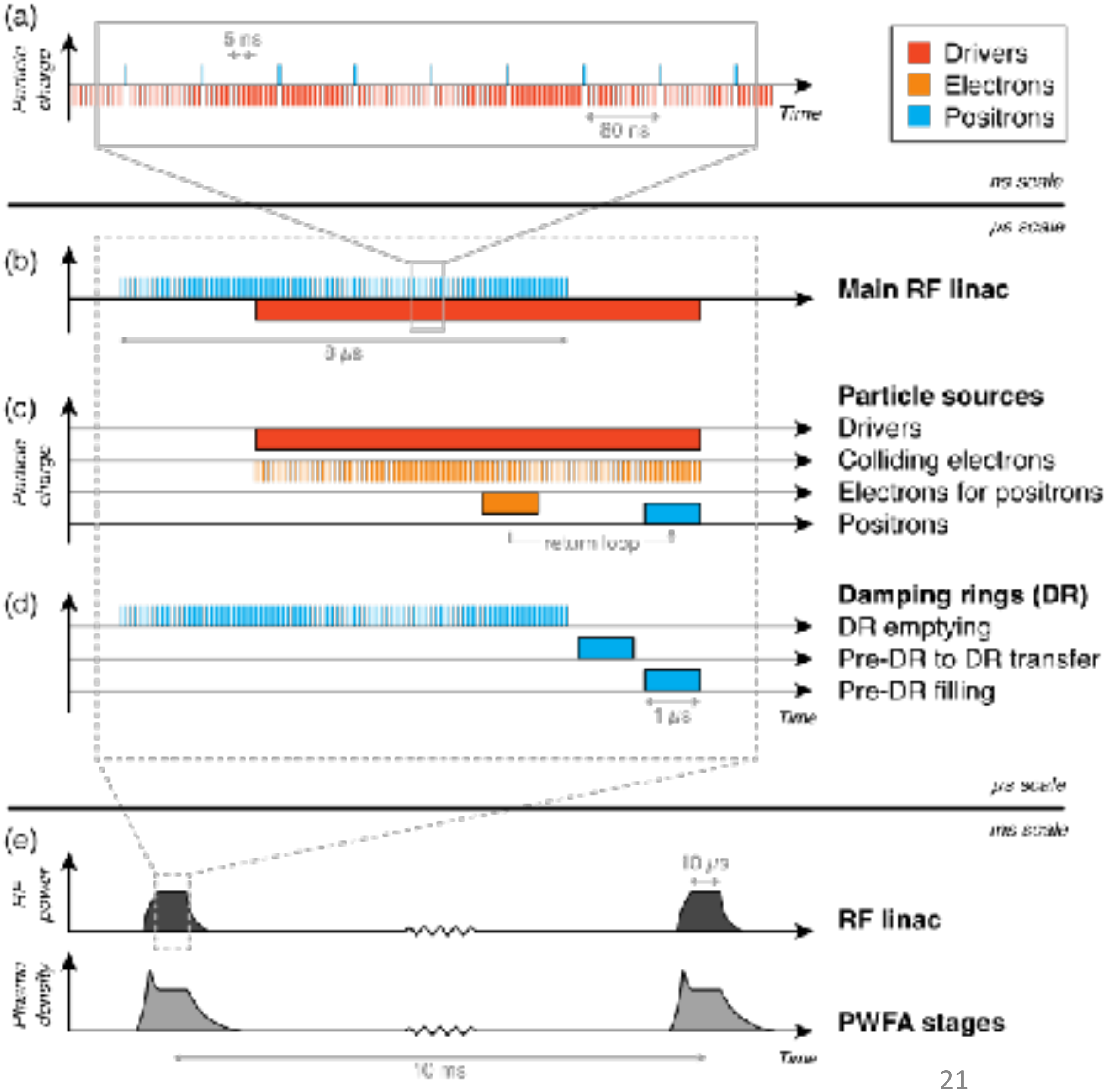
- Drivers go through turn-around and then distributed to plasma cells via undulating delay chicane.
- Assuming TR ~ 1, e- bunch accelerated by 31 GeV/5m stage => 16 stages with $\rho \sim 7*10^{15}$ => 6.4 GV/m.
- Interstage optics needs ~ <26.5m> but scales with sqrt(E); <gradient>~1.2 GV/m
- Total length of PWFA linac = 410m.



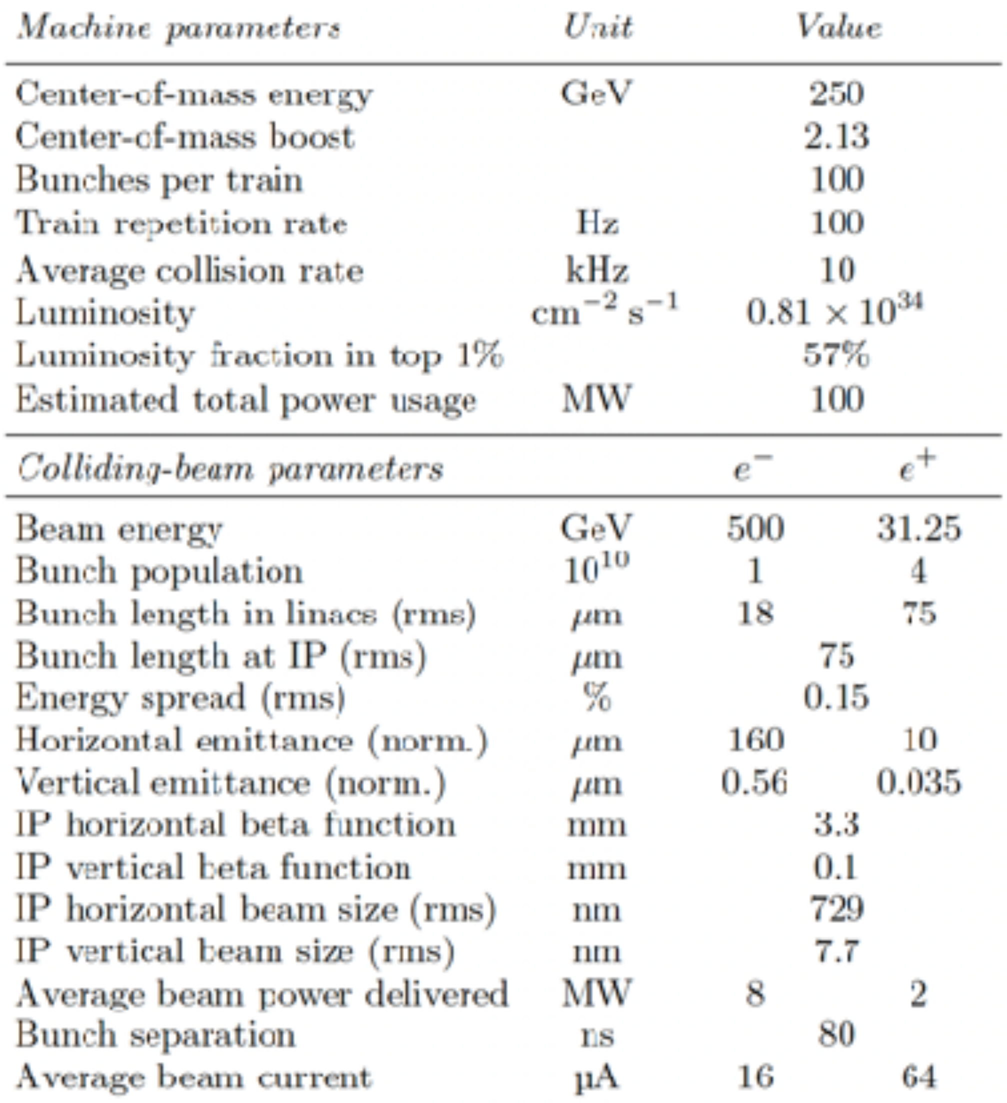
Bunch-train pattern.



- Assuming L-band linac:

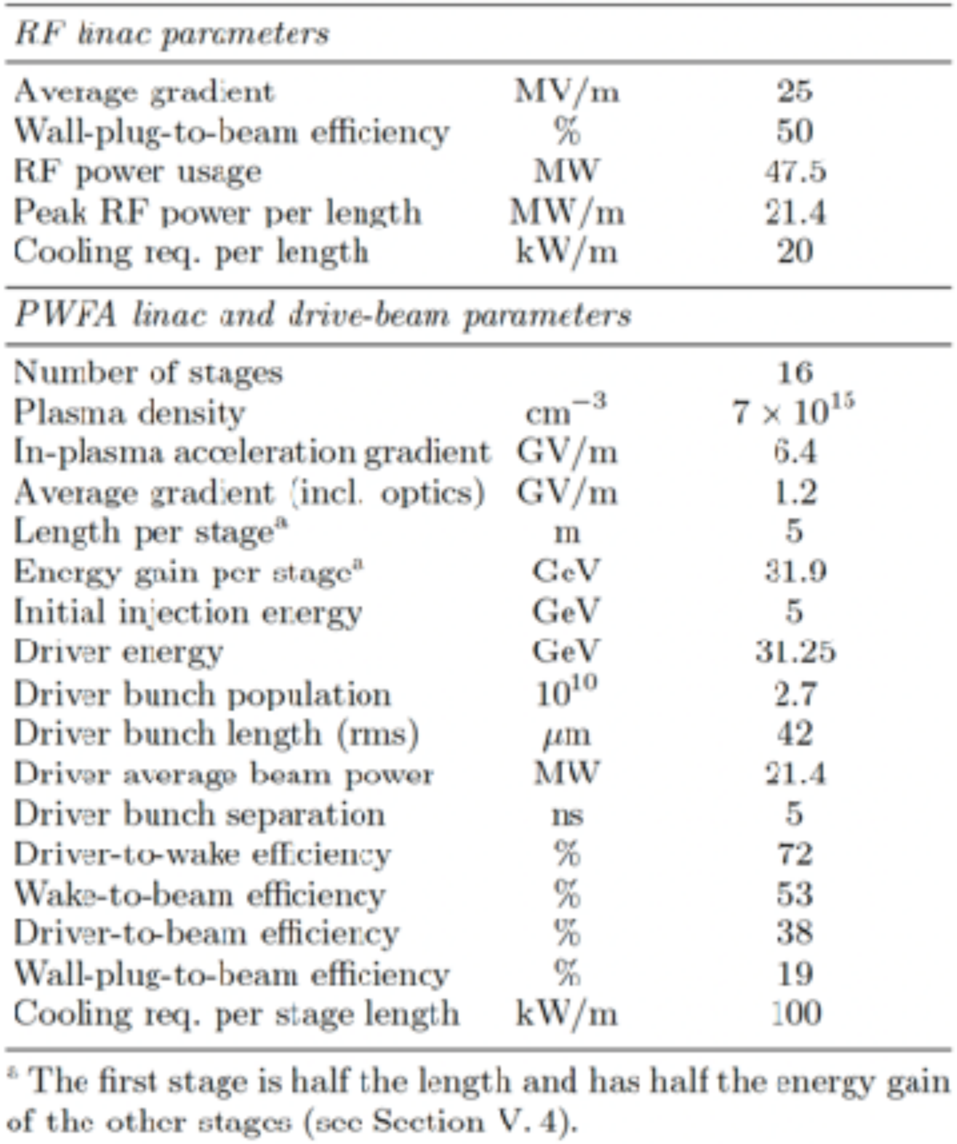


HALHF Parameter Table



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

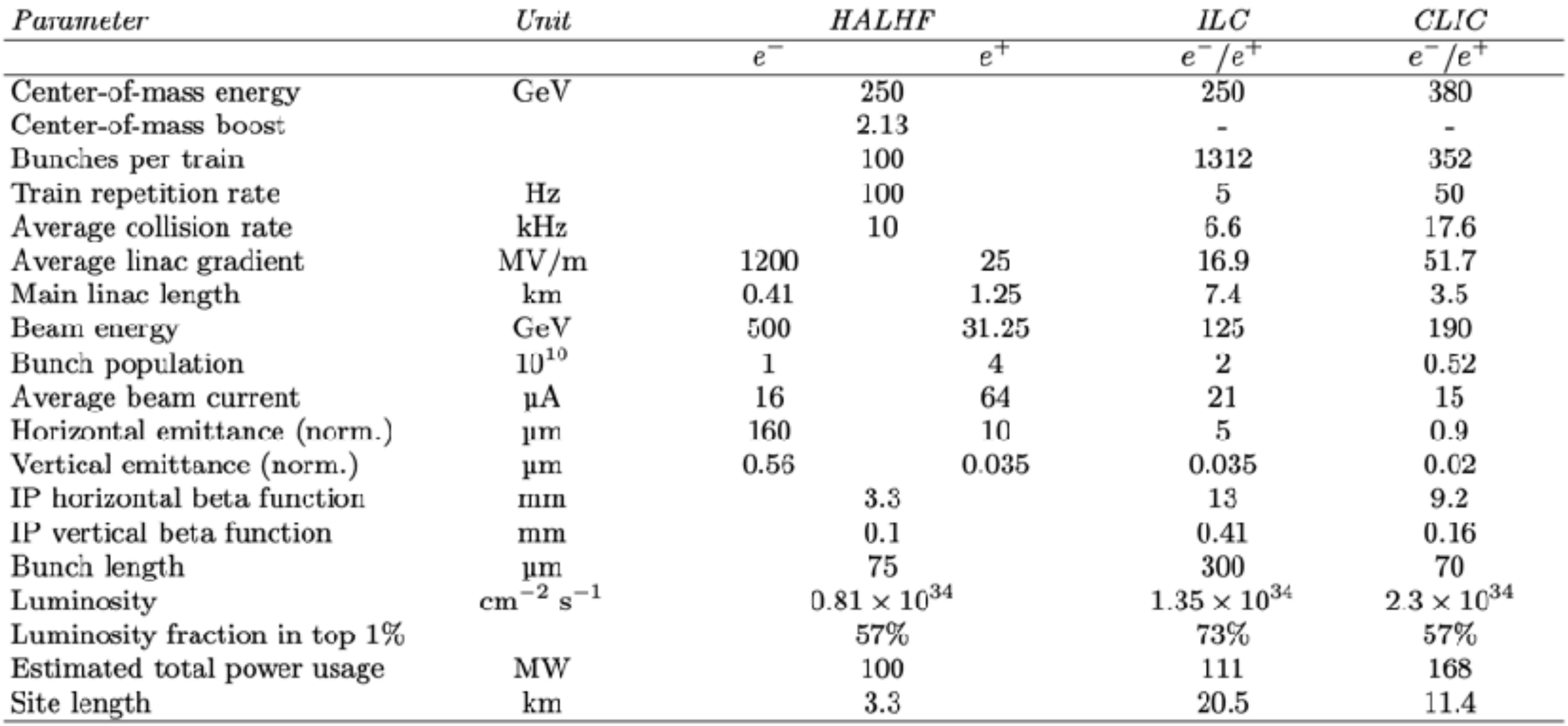


RF linac parameters		
Average gradient	MV/m	25
Wall-plug-to-beam efficiency	%	50
RF power usage	MW	47.5
Peak RF power per length	MW/m	21.4
Cooling req. per length	kW/m	20

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

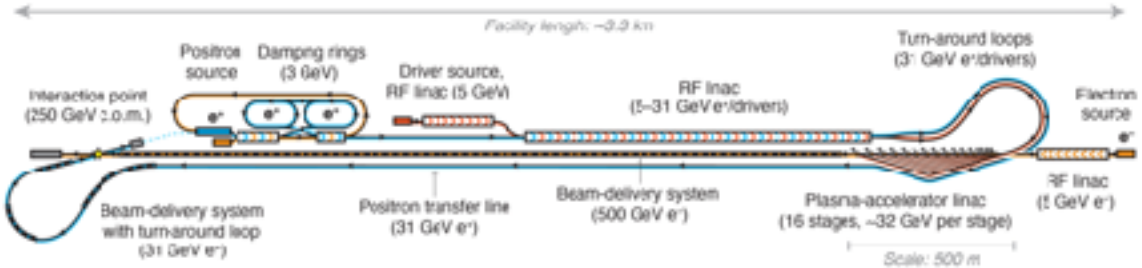
[a] The first stage is half the length and has half the energy gain of the other stages (see Section V. 4).

HALHF Parameters cf ILC & CLIC

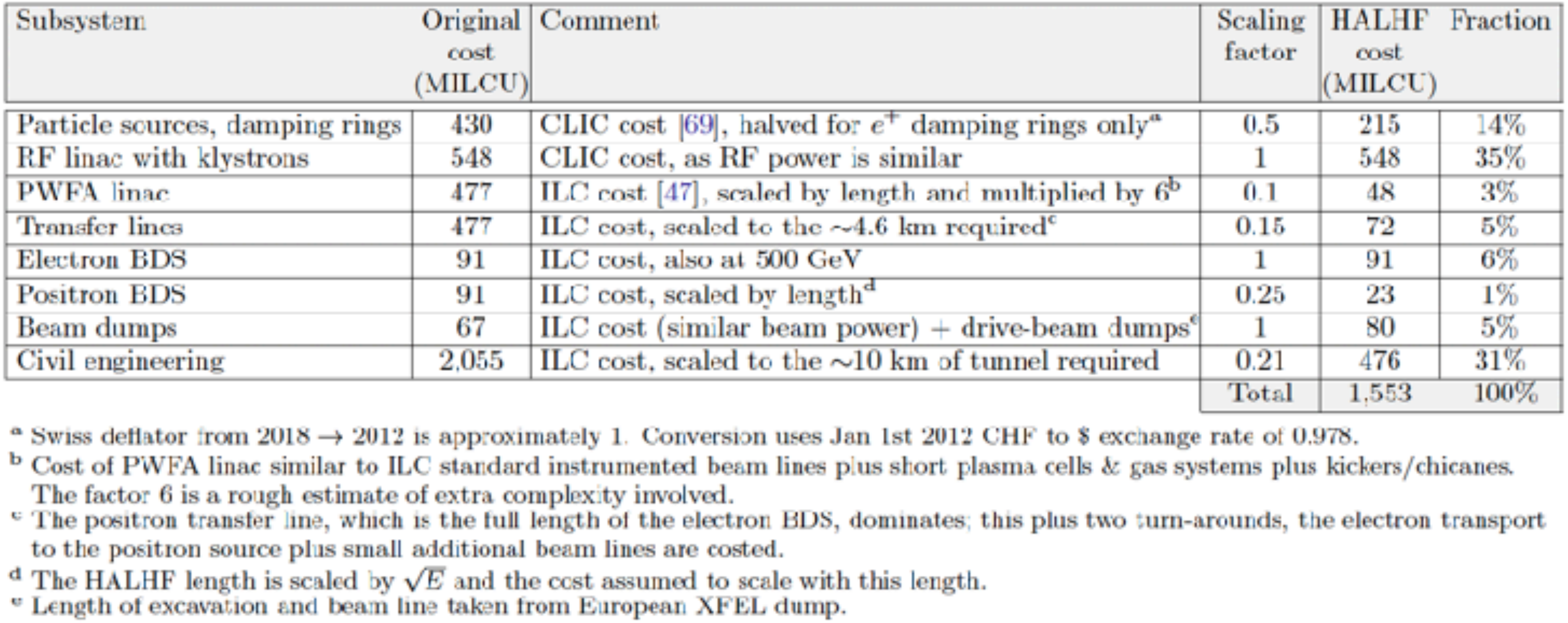


Parameter	*Unit*	*HALHF*		*ILC*	*CLIC*
		e^-	e^+	e^-/e^+	e^-/e^+
Center-of-mass energy	GeV	250		250	380
Center-of-mass boost		2.13		-	-
Bunches per train		100		1312	352
Train repetition rate	Hz	100		5	50
Average collision rate	kHz	10		6.6	17.6
Average linac gradient	MV/m	1200	25	16.9	51.7
Main linac 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	$\text{cm}^{-2}\ \text{s}^{-1}$	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

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.

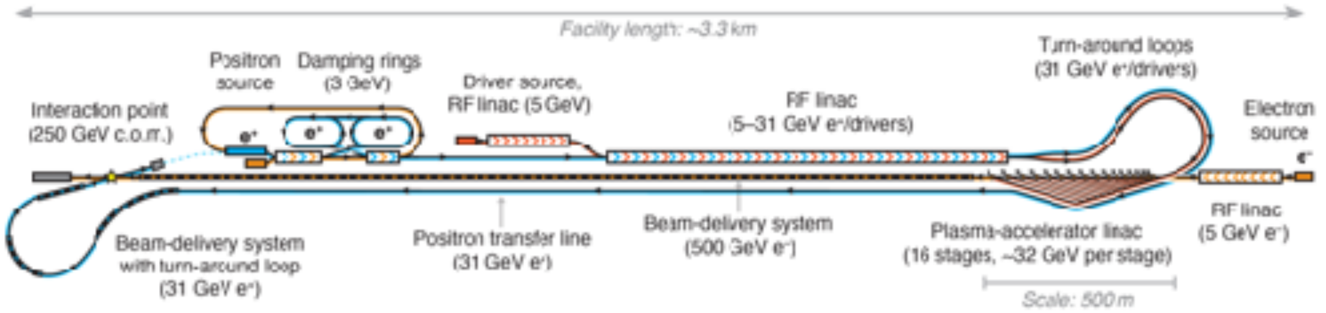
[b] Cost of PWFA linac similar to ILC standard instrumented beam lines plus short plasma cells & gas systems plus kickers/chicanes. The factor 6 is a rough estimate of extra complexity involved.

[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.

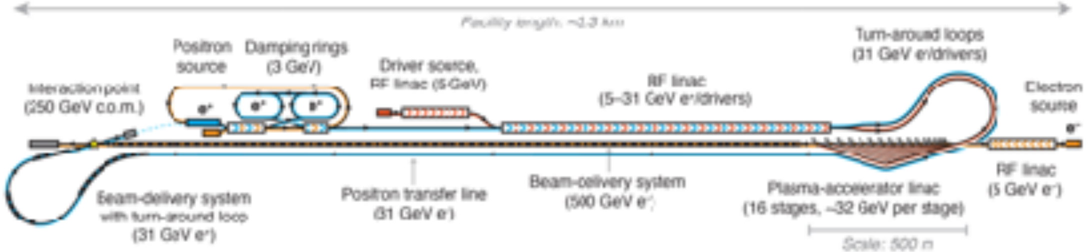
[e] Length of excavation and beam line taken from European XFEL dump.

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.

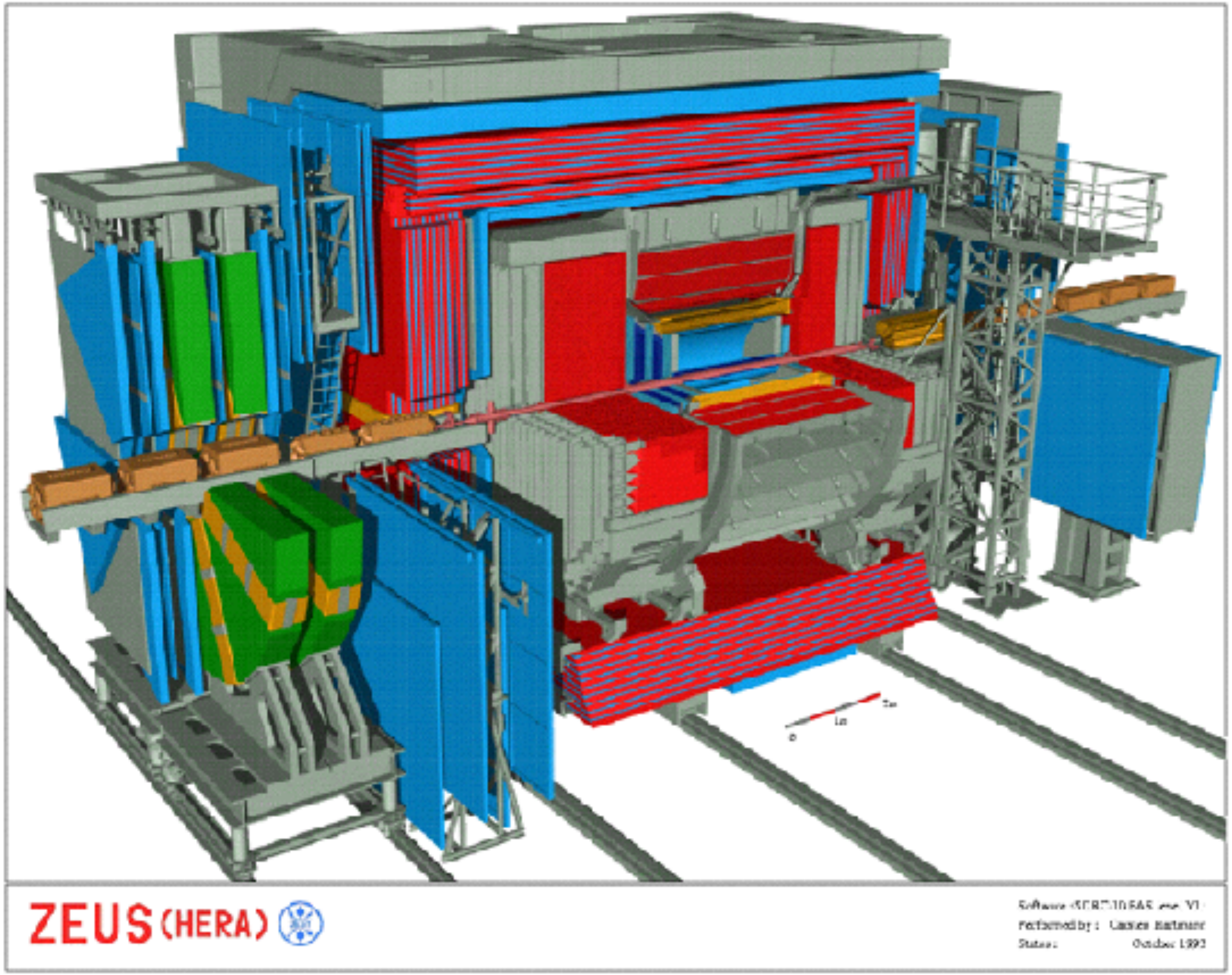
Running Costs



- 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.

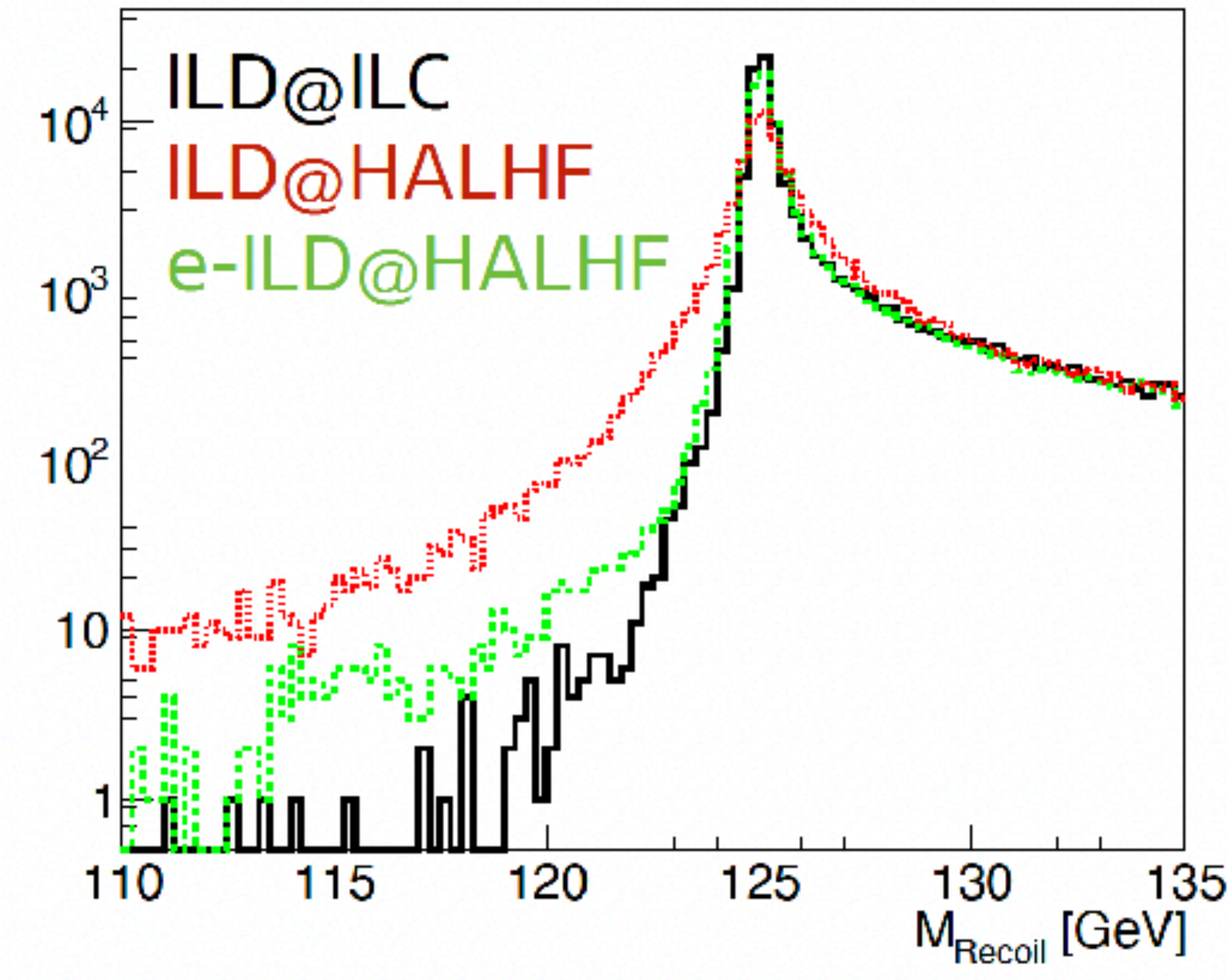
Experimentation at HALHF

- Boost is smaller than HERA - HERA detectors very similar to those at symmetric machines.
- 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

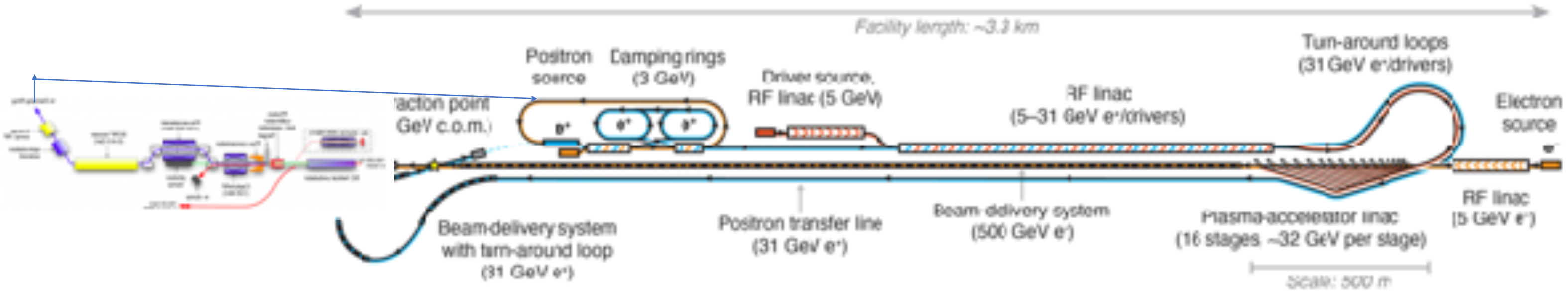


Experimentation at HALHF

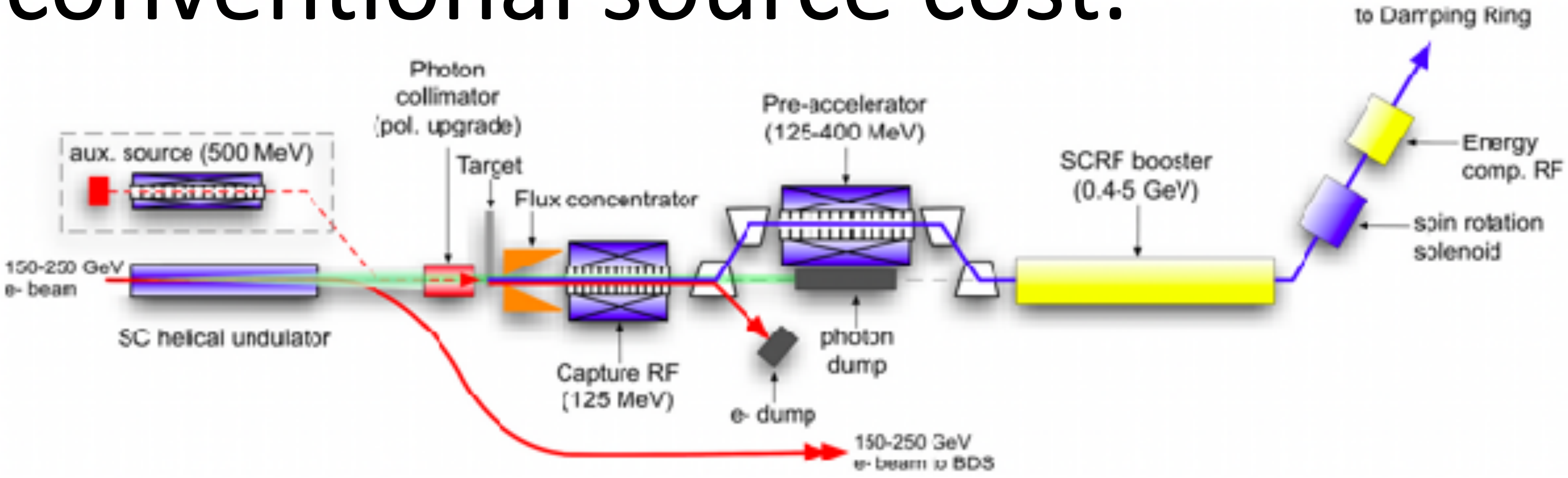
- Preliminary study (M. Berggren, A. Laudrain(DESY)) with long ILD barrel: ~ 20% degradation of Higgs resolution.
- "Proper" detector design required.



Upgrades



- Produce e^+ polarization via ILC-like scheme - ideas exist for $E(e^-)$ 500 GeV; wiggler probably longer and more expensive. Cost ~ 300 MILCU minus conventional source cost.



Energy Upgrades

- Either keep e^+ energy same increases γ as E increases – experiments more and more difficult; or increase e^+ energy to keep γ ~ constant => more expensive linac.
- However, getting to ttbar (380 GeV) with same e^+ energy => E(e-) ~ 1.165 TeV and γ ~ 3.1, ~ HERA and ttbar final state even more spherical. However, running costs increase with γ and there is a limit to beam-current asymmetry possible because of e^+ production => unattractive.

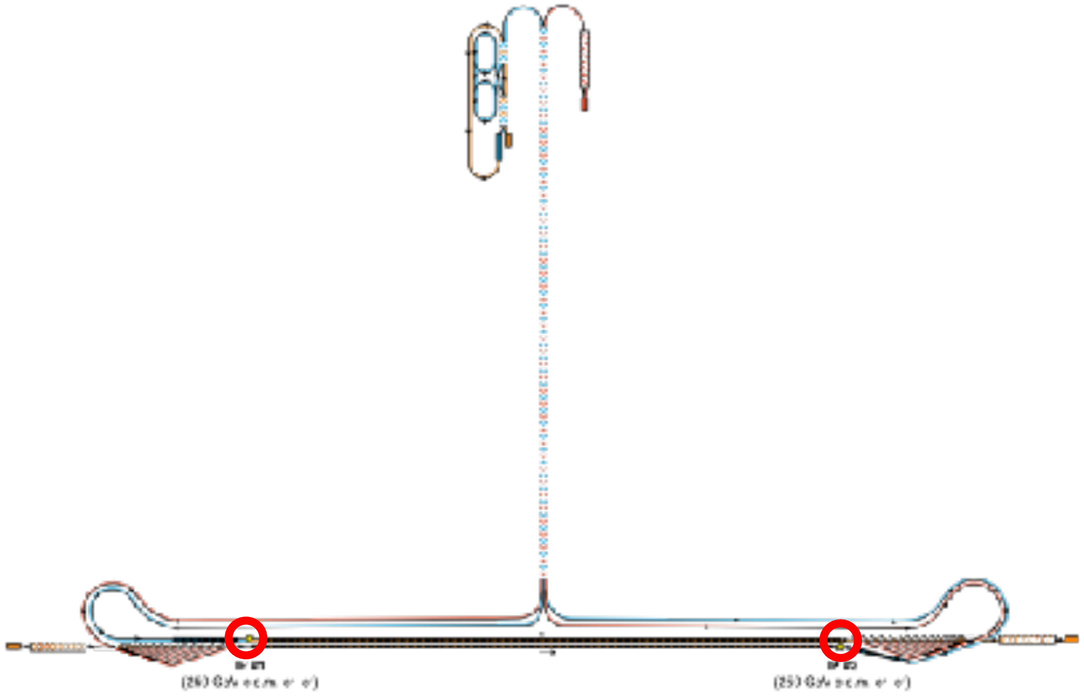
Energy Upgrades

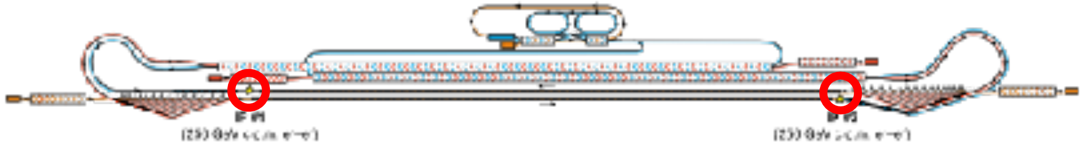
- Keeping γ constant by lengthening conventional linac - needs E(e^+) ~ 47.5 GeV and E(e^-) ~ 760 GeV. (space allocated and tunnel would be built at initial HALHF construction time both for linac &BDS).
- Increases length of linac by 50%; PWFA arm also increases as inter-stage optics proportional to sqrt(E) => +130 m. Capital cost ~ +200 MILCU; running costs increase by 25% to ~125 MW.

NB. Preliminary!

2-IP Upgrade

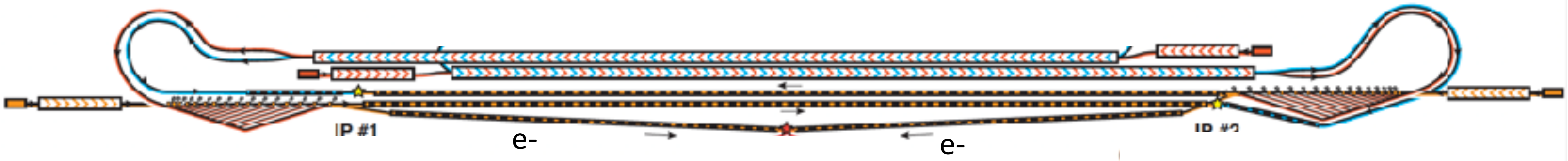
- Unlike circular machines, in LCs, extra IPs just share **L**. CLIC has only 1 detector; ILC has 2 “oscillating” ones.
- HALHF can either share **L** or double it – with an extra linac!
- Cost: T-shape: larger footprint - 250 MILCU; 2linac - 690 MILCU
- Running costs @ Higgs: T-shape: same; 2linac – 150 MW

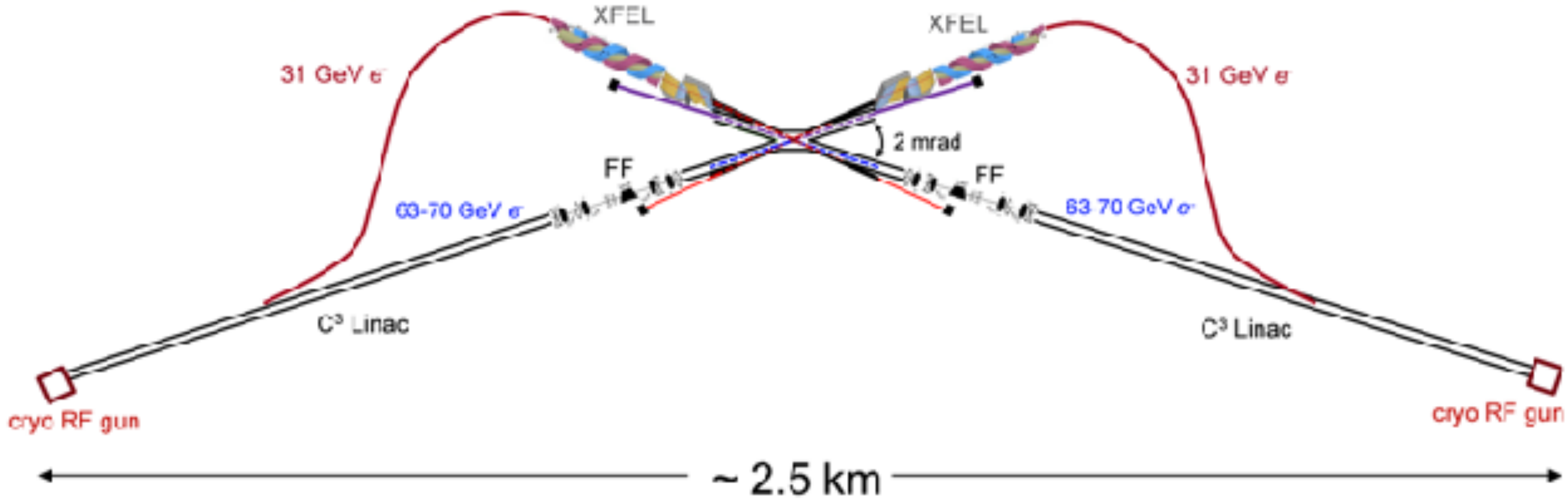




γ γ & Multi-TeV Upgrade

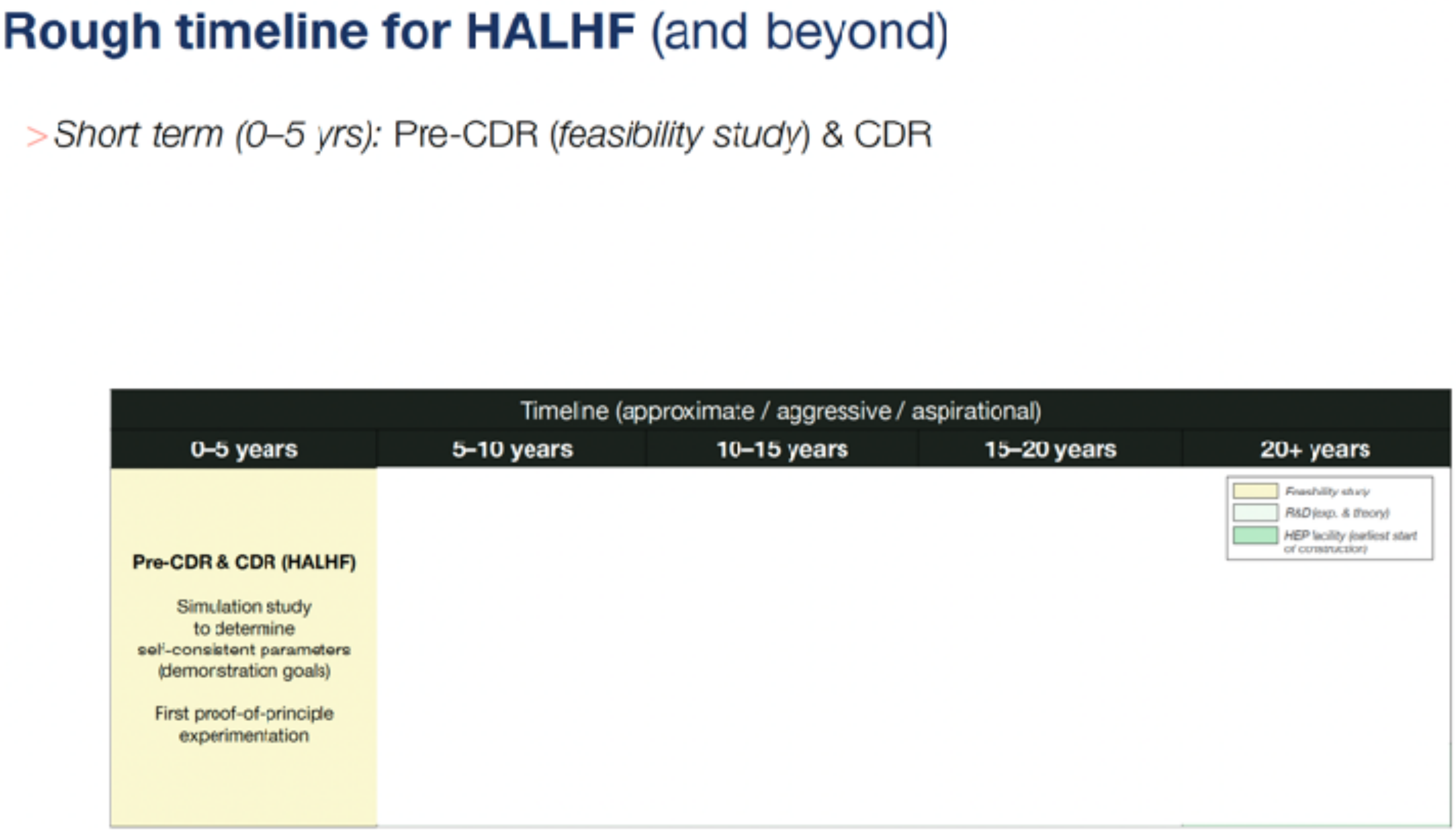
- Symmetry restoration!
  - γ γ from Compton backscattering via lasers
  - But not yet available - use XFEL driven by PWFA drive beams – XCC idea of Barklow et al.





Barklow et al,
arXiv:2203.08484
Snowmass21

R&D Required



Rough timeline for HALHF (and beyond)

- *Short term (0–5 yrs):* Pre-CDR (*feasibility study*) & CDR

Timeline (approximate / aggressive / aspirational)				
0–5 years	**5–10 years**	**10–15 years**	**15–20 years**	**20+ years**
Pre-CDR & CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals) First proof-of-principle experimentation				

🟨 *Feasibility study*

⬜ *R&D* (exp. & theory)

🟩 *HEP* facility (earliest start of construction)

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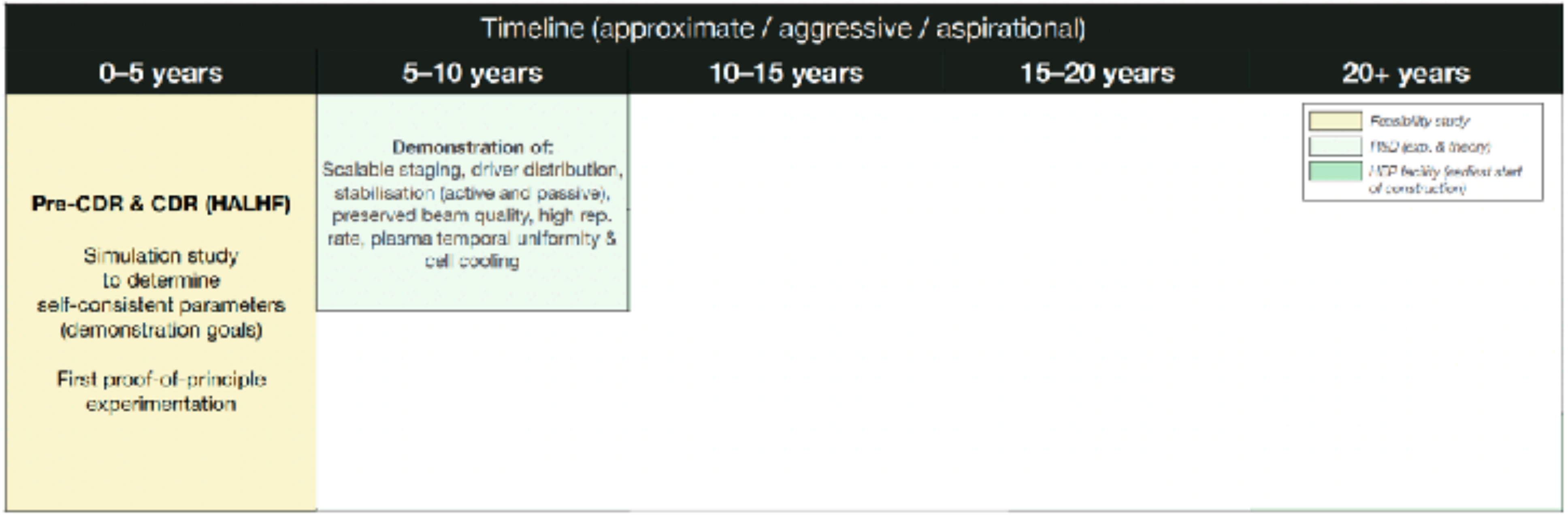
R&D Required

- *Short term (0–5 yrs):* Pre-CDR (*feasibility study*) & CDR
- *Near term (5–10 yrs):* Much Plasma R&D required!



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0–5 years	5–10 years	10–15 years	15–20 years	20+ years
Pre-CDR & CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals) First proof-of-principle experimentation	Demonstration of: Scalable staging, driver distribution, stabilisation (active and passive), preserved beam quality, high rep. rate, plasma temporal uniformity & cell cooling			

🟨 Feasibility study
⬜ R&D (exp. & theory)
🟩 HEP facility (earliest start of construction)

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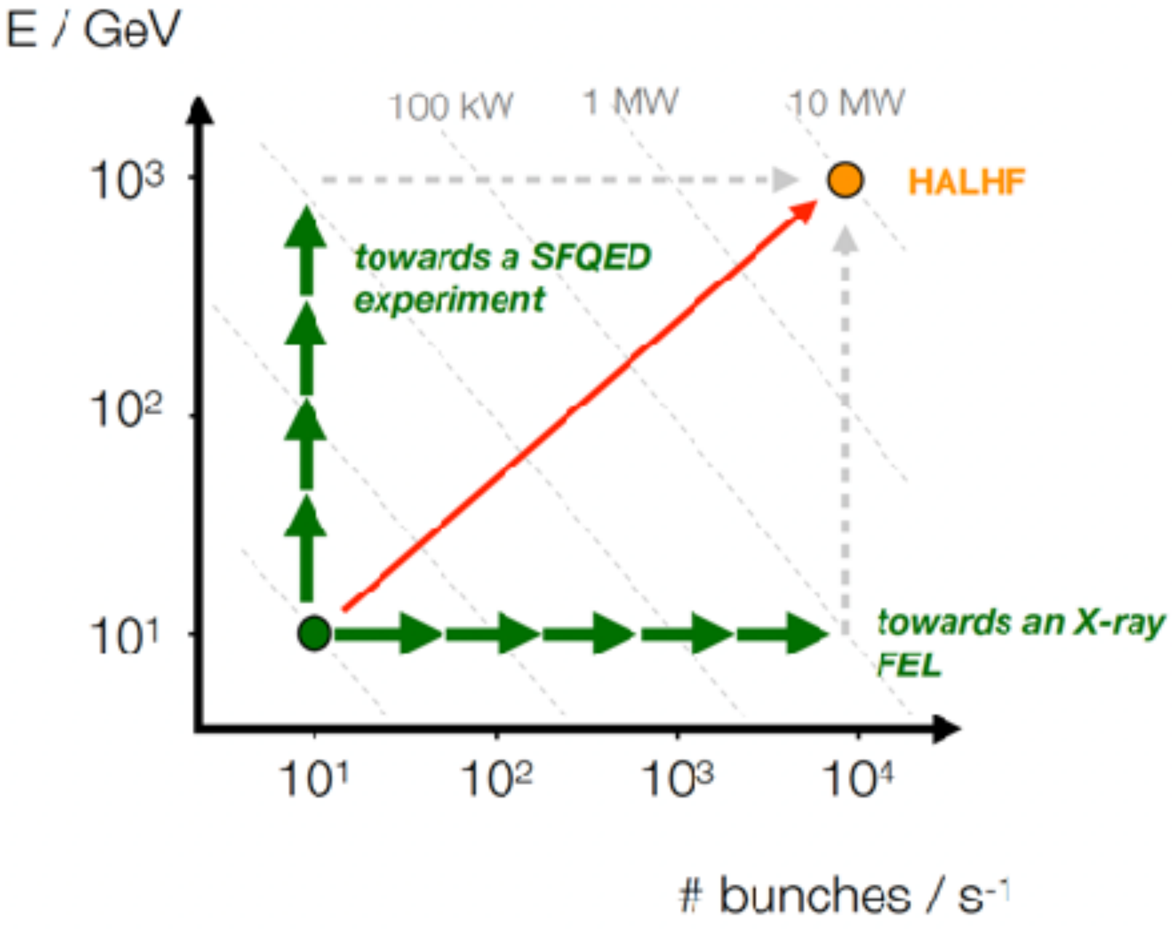
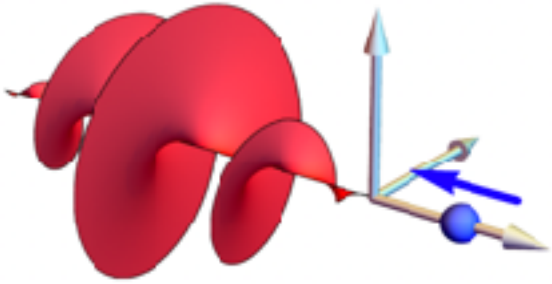
Path to construction

- “Valley of death” in performance goal requires decoupled strategy.



Strong-field QED



Source: Blackburn et al., Phys. Plasmas 25, 083108 (2018)

X-ray FEL

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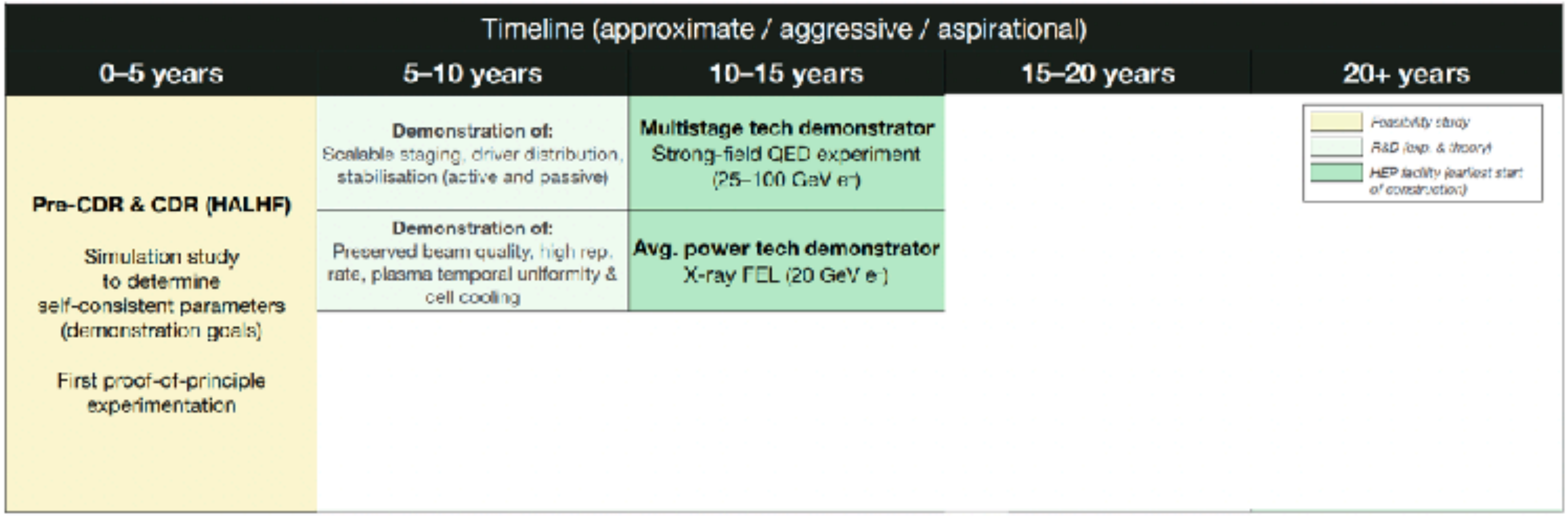
Path to construction

- *Short term (0–5 yrs):* Pre-CDR (*feasibility study*) & CDR
- *Near term (5–15 yrs):* Tech. Demonstrators — **strong-field QED** and an **X-ray FEL**



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	Demonstration of: Preserved beam quality, high rep. rate, plasma temporal uniformity & cell cooling	**Avg. power tech demonstrator** X-ray FEL (20 GeV e^-)		

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Path to construction

- *Short term (0–5 yrs):* Pre-CDR (*feasibility study*) & CDR
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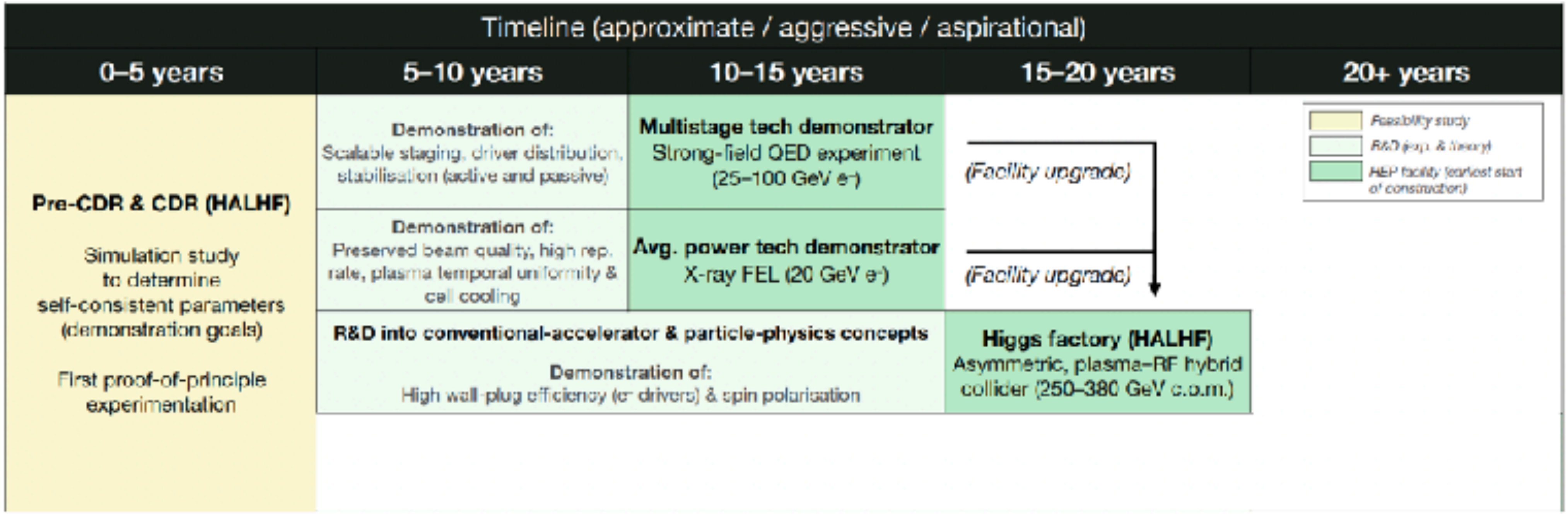
- *Long term (15–20 yrs):* Delivery of HALHF — **intense R&D required**



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	Demonstration of: Preserved beam quality, high rep. rate, plasma temporal uniformity & cell cooling	**Avg. power tech demonstrator** X-ray FEL (20 GeV e^-)	*(Facility upgrade)*	
	R&D into conventional-accelerator & particle-physics concepts **Demonstration of:** High wall-plug efficiency (e^- drivers) & spin polarisation		**Higgs factory (HALHF)** Asymmetric, plasma–RF hybrid collider (250–380 GeV c.o.m.)	

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Path to construction

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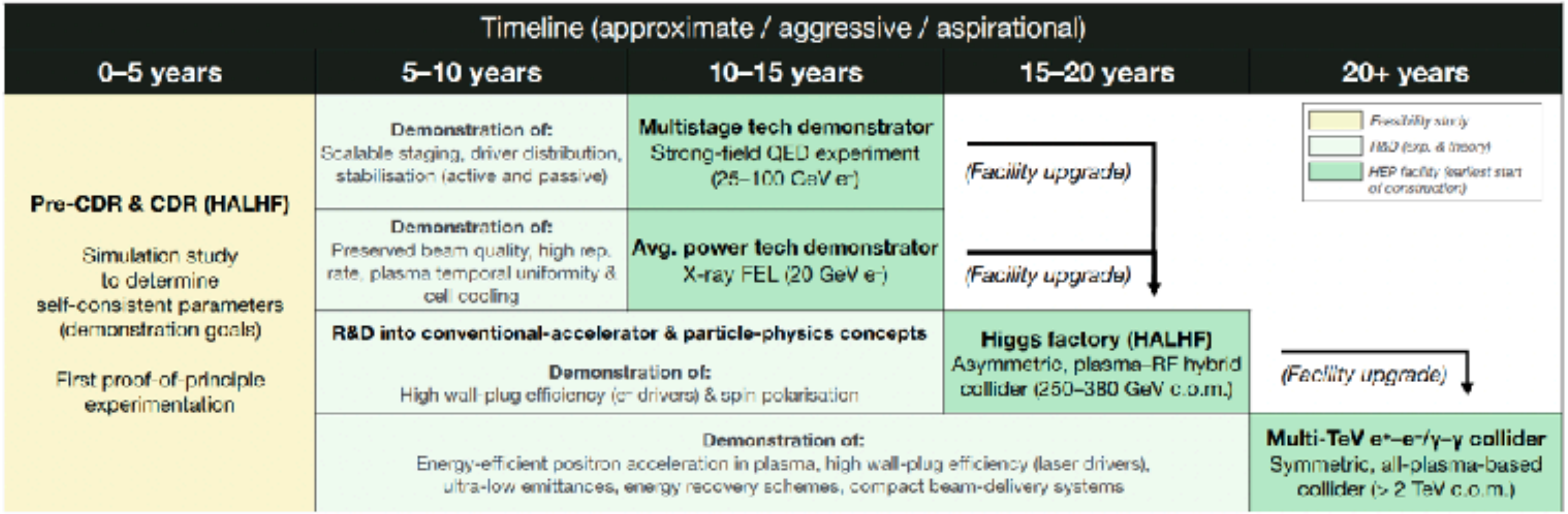
- *Near term (5–15 yrs):* Tech. Demonstrators — **strong-field QED** and an **X-ray FEL**
- *Long term (15–20 yrs):* Delivery of HALHF — **intense R&D required**
- *Upgrades (20+ yrs):* Upgrade path for HALHF (many options available)



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	Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser drivers), ultra-low emittances, energy recovery schemes, compact beam-delivery systems			**Multi-TeV e^+–e^-/γ–γ collider** Symmetric, all-plasma-based collider (> 2 TeV c.o.m.)

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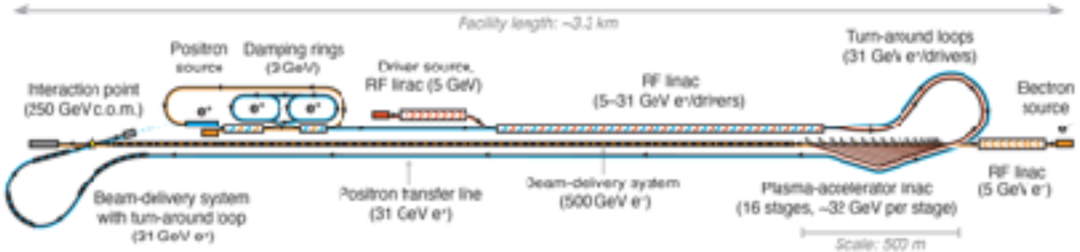
Summary & Outlook



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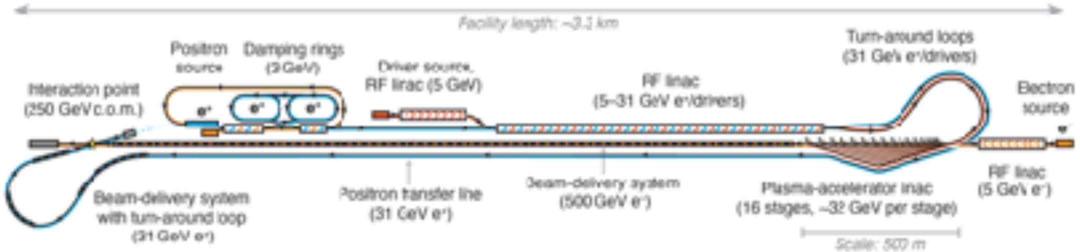
Summary & Outlook



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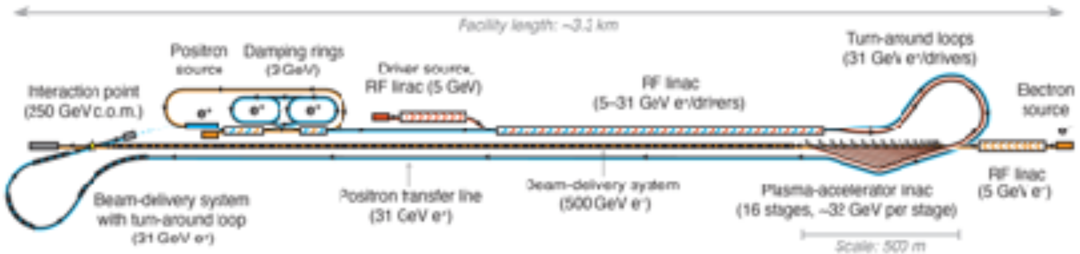
- Even if e^+ acceleration not a problem, HALHF could still be best way forward – but requires > a decade of significant R&D.

Summary & Outlook



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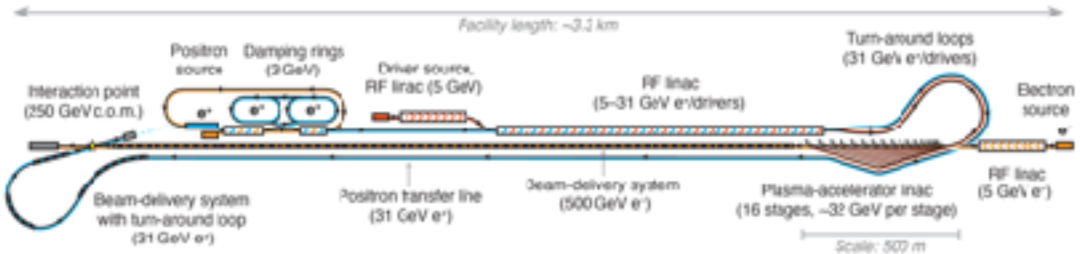
Summary & Outlook



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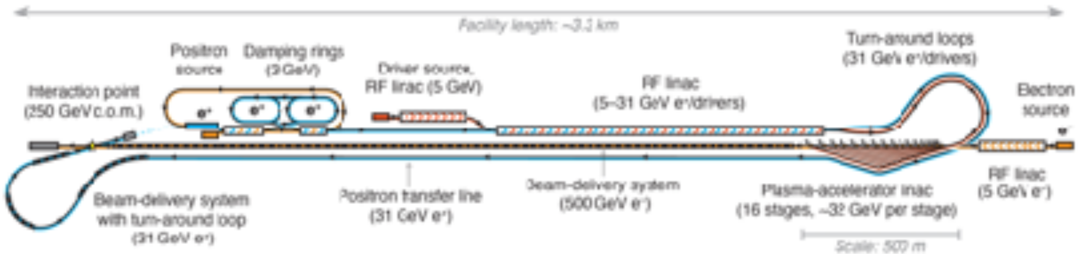

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- Better start asap – HALHF "kick-off" meeting @ DESY on 23.10.23