

IAS PROGRAM

Fundamental Physics

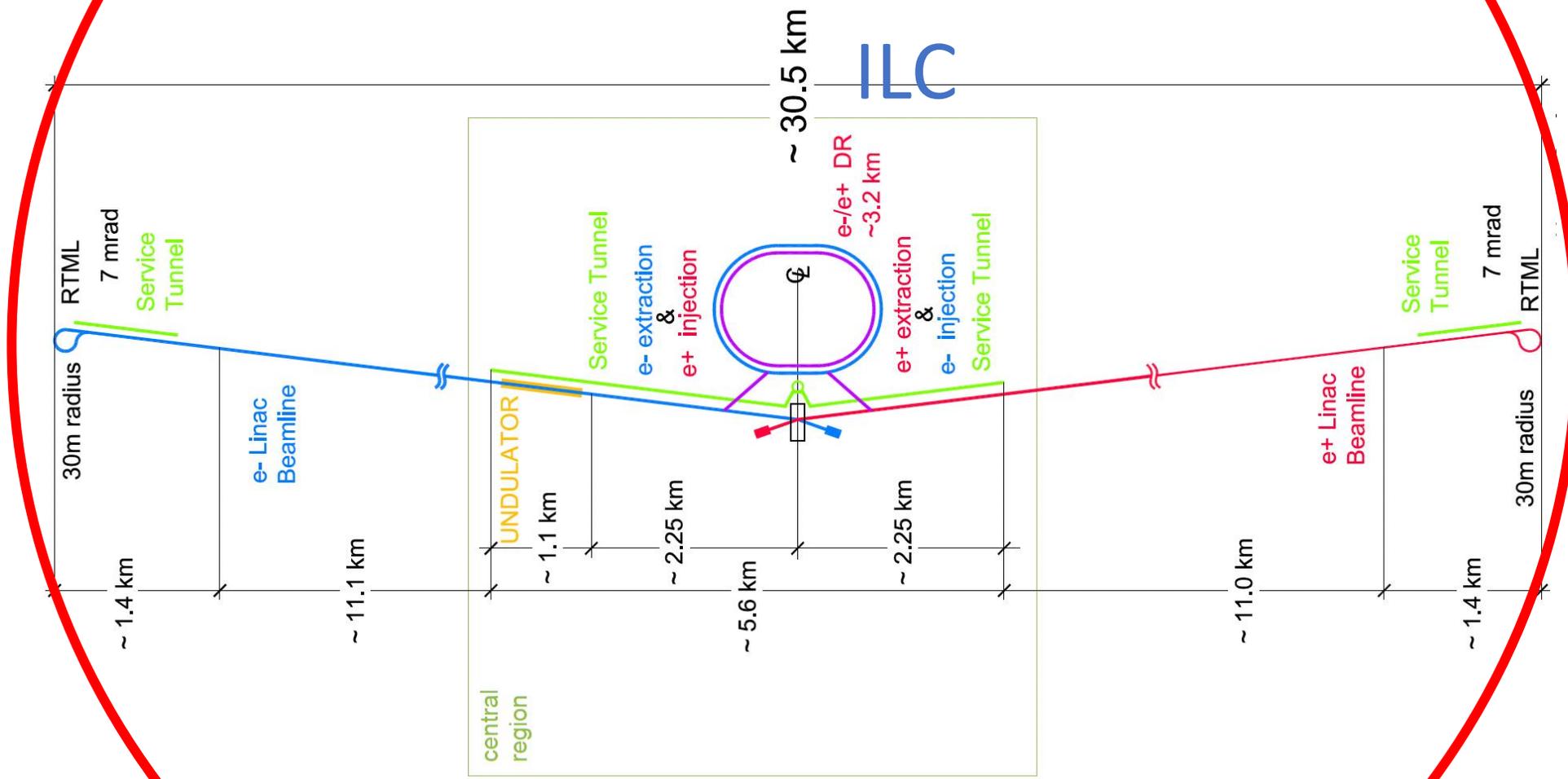
January 12-16, 2026

A Hybrid Asymmetric Linear Higgs Factory

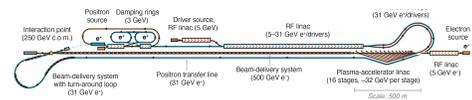


Brian Foster (Oxford/DESY)

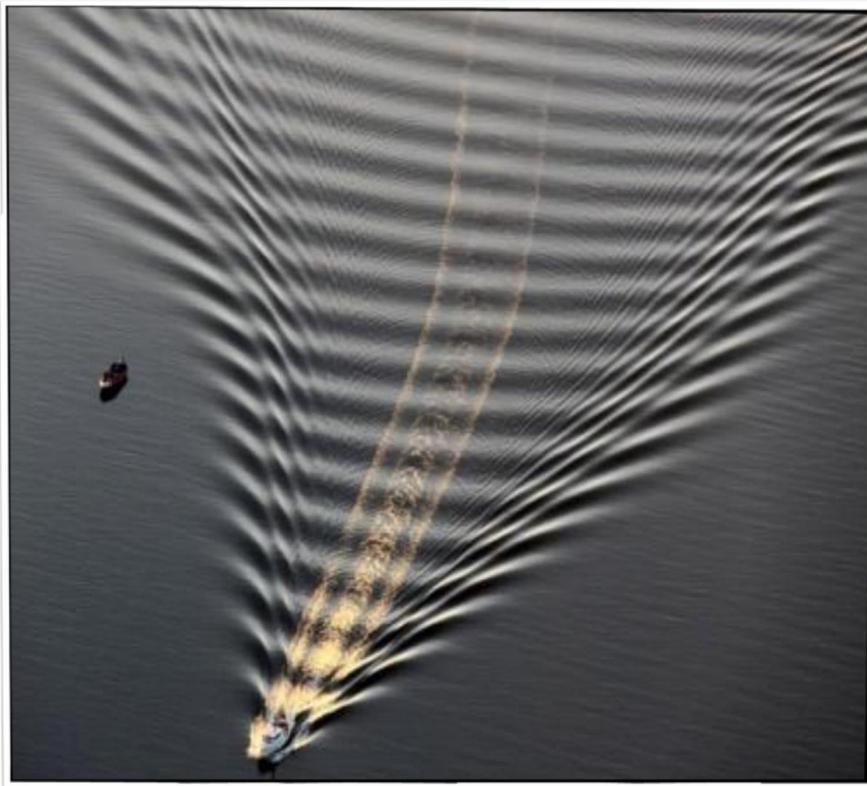
Hybrid Asymmetric Linear Higgs Factory (HALHF)



CEPC



Plasma Wave Acceleration



Wake excitation



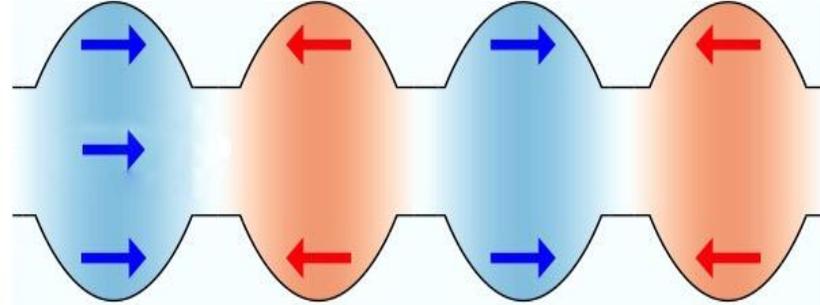
Particle injection



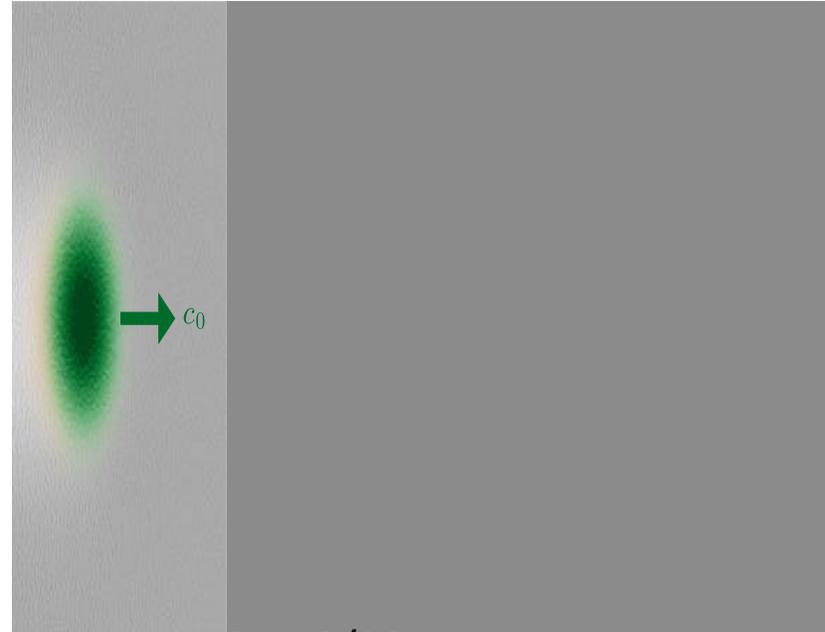
Plasma vs SCRF Cavities



SCRF Cavity



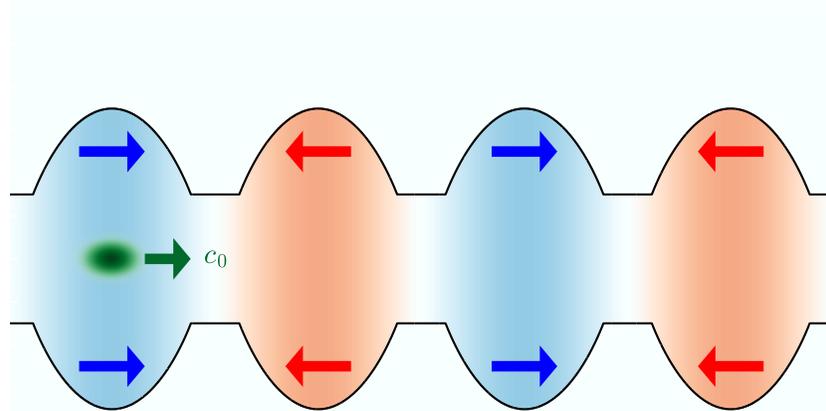
Plasma
wakefield



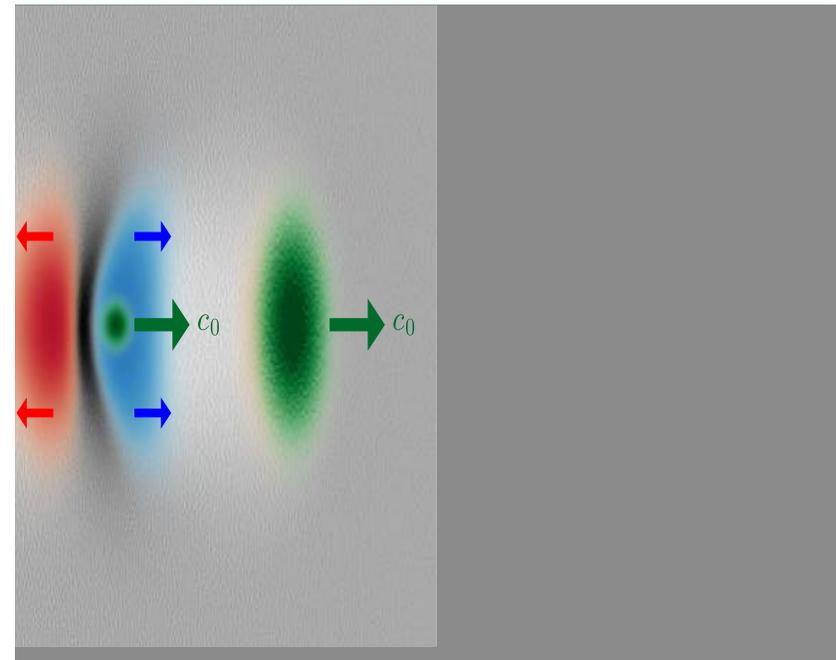
B. Foster, UCL, 10/23

Plasma vs SCRF Cavities

SCRF Cavity

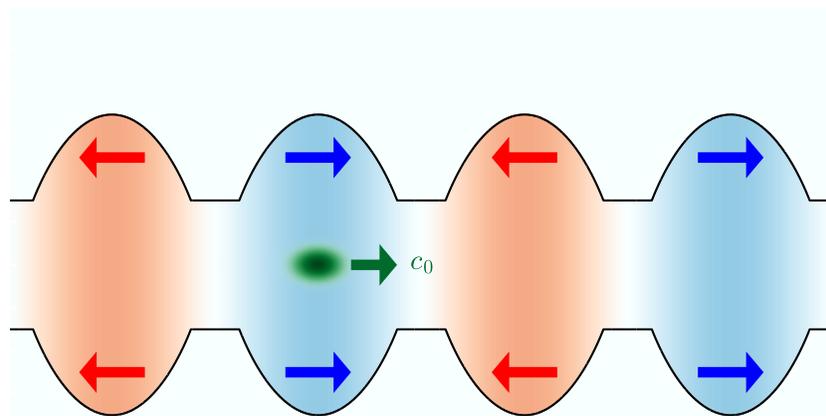


Plasma
wakefield

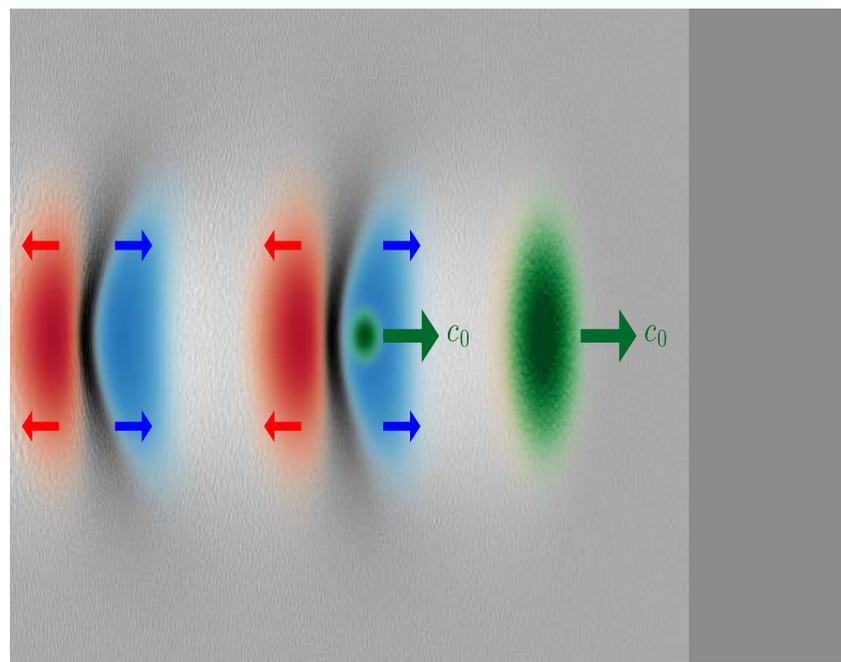


Plasma vs SCRF Cavities

SCRF Cavity



Plasma
wakefield



Setting the scale

Plasma frequency depends only on density

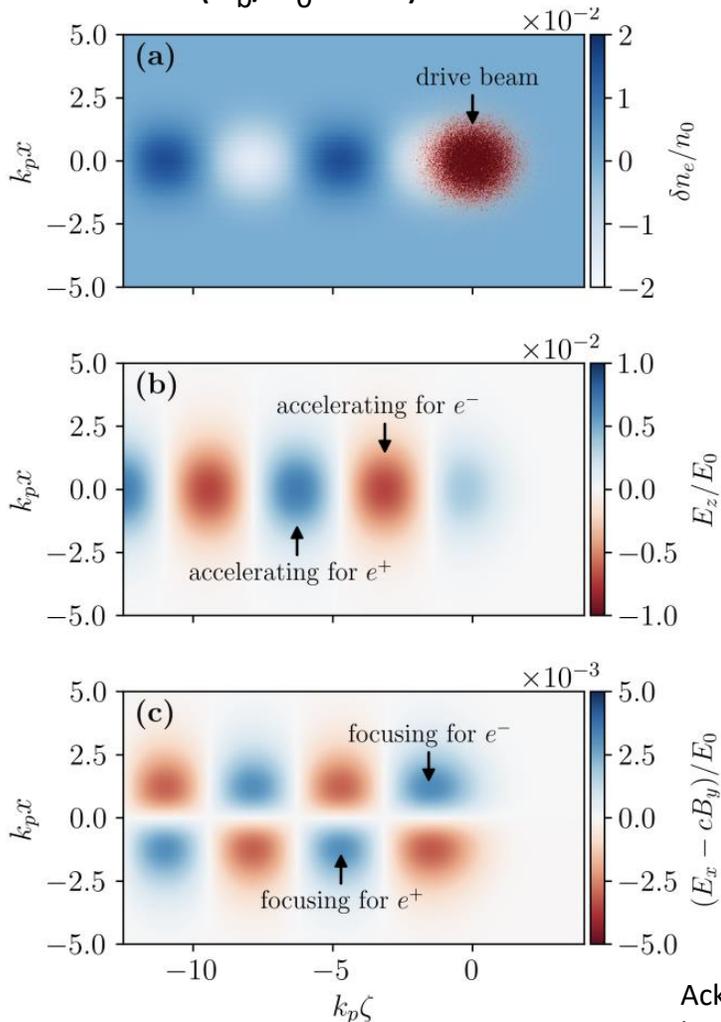
$$\omega_p^2 = \frac{4\pi n_p e^2}{m}$$

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

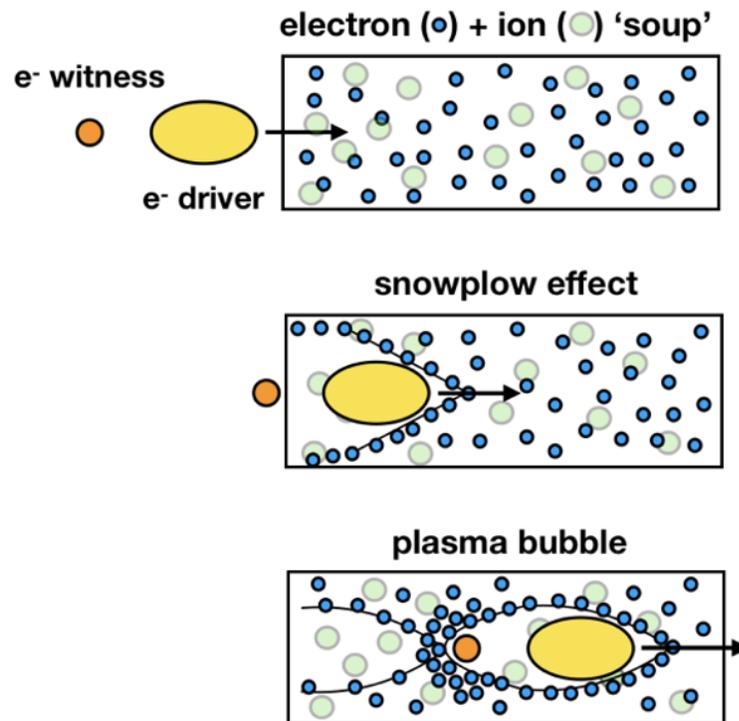
$$\lambda_p = \frac{2\pi}{k_p} = 1mm \sqrt{\frac{1 \cdot 10^{15} \text{ cm}^{-3}}{n_p}}$$

Plasma Acceleration 101

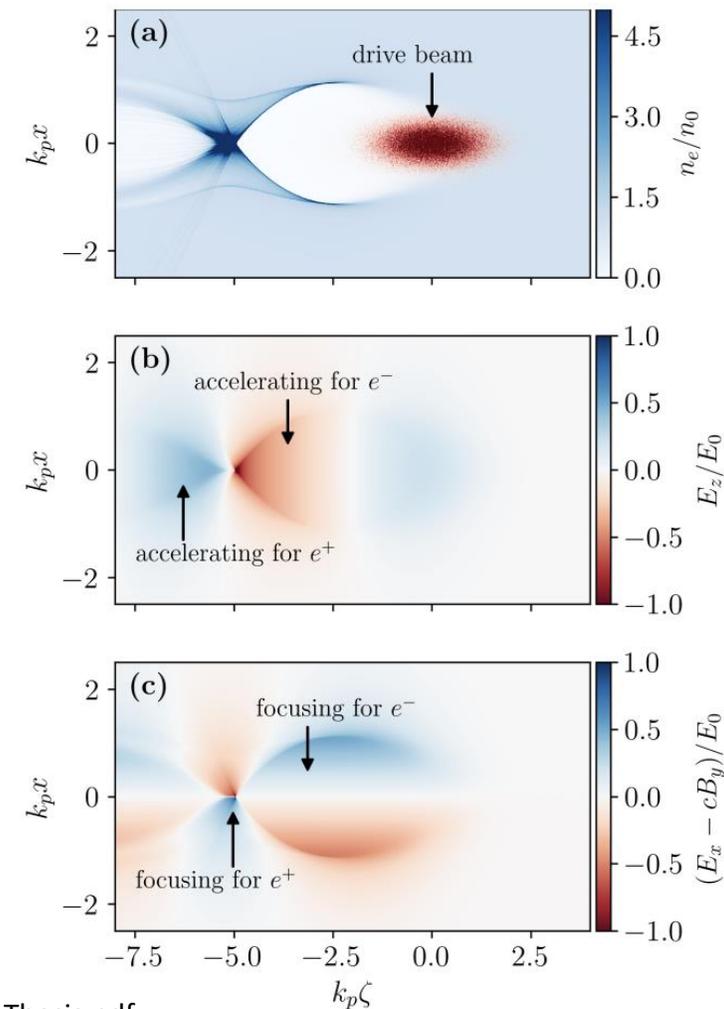
Linear Regime
($n_b/n_0 \ll 1$)



Non-linear (“Blow-out”) Regime ($n_b/n_0 \gg 1$)



Non-linear (“Blow-out”) Regime ($n_b/n_0 \gg 1$)



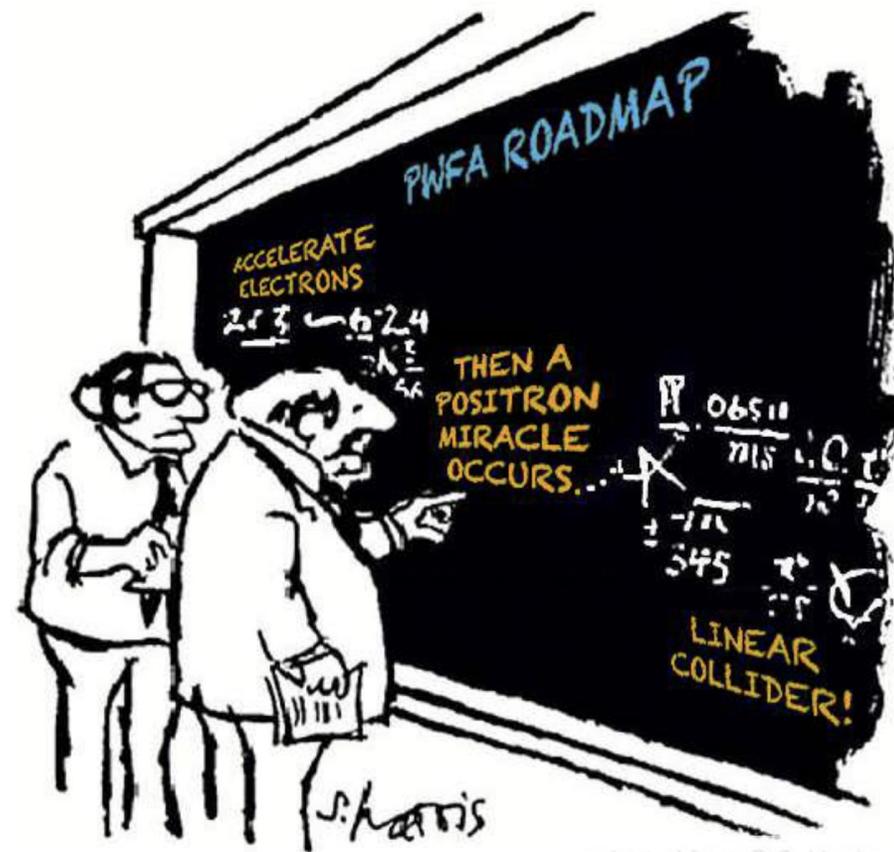
time

Ack. For next 3 slides: S. Deiderichs:
<https://ediss.sub.uni-hamburg.de/bitstream/ediss/10403/1/SDiederichs-PhD-Thesis.pdf>

Key motivation: Positron acceleration in plasma

One of the biggest unsolved problem in plasma acceleration

- > Plasmas are charge asymmetric
 - > No “blowout regime” for e^+
- > Positron acceleration has been demonstrated experimentally.
 - > However, luminosity per power still orders of magnitude below RF and e^- PWFA.

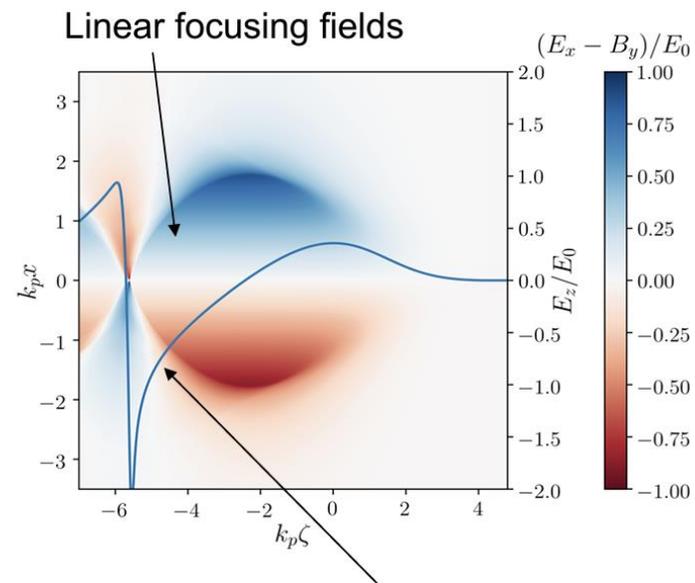
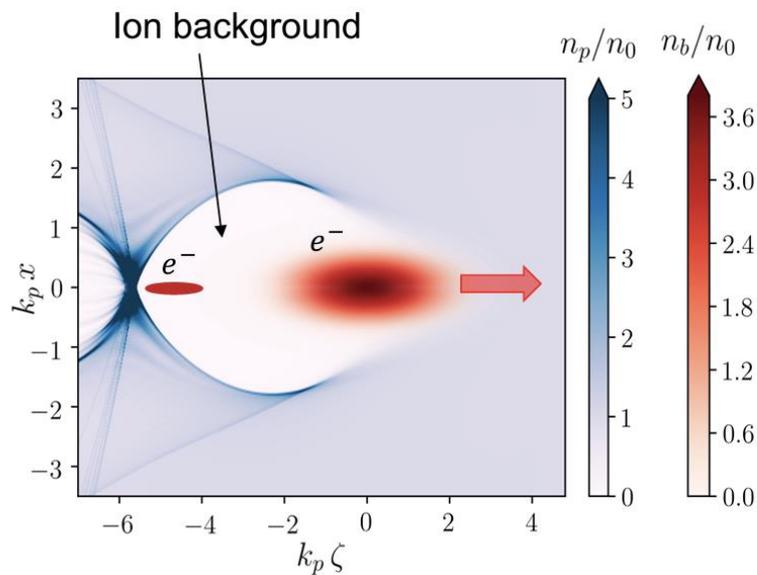


adapted from © S. Harris

“I think you should be more explicit here in step two.”

Positron acceleration

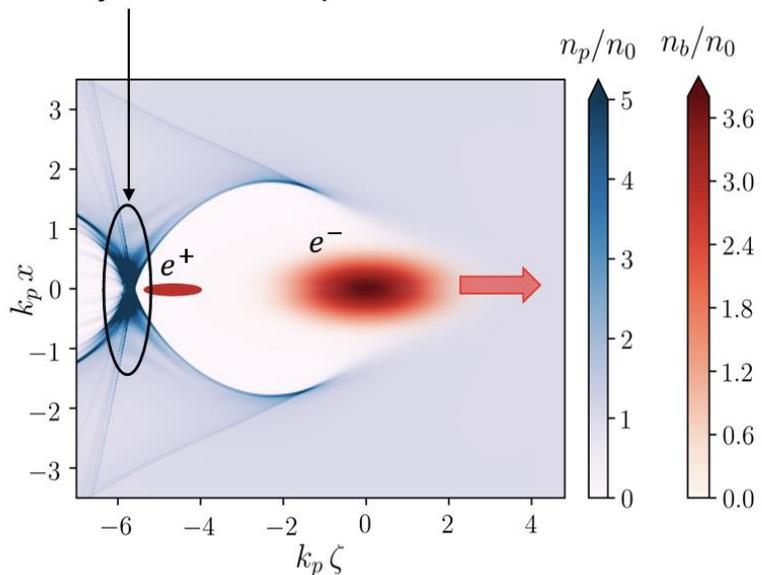
e^-



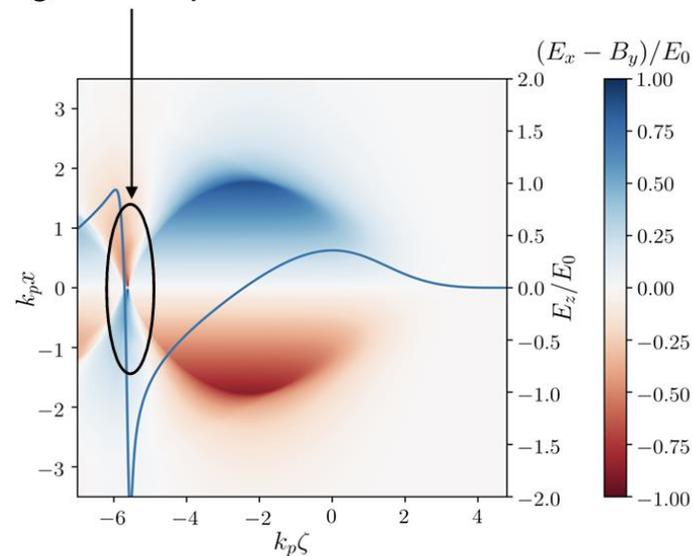
Strong accelerating fields

e^+

High density electron cusp

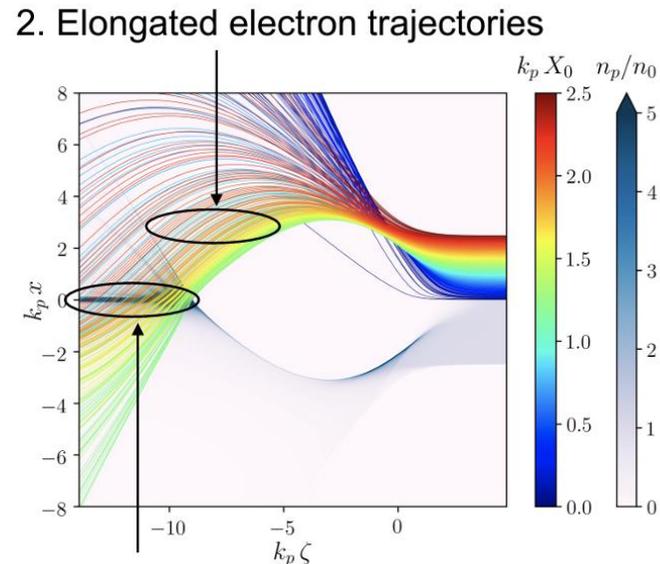
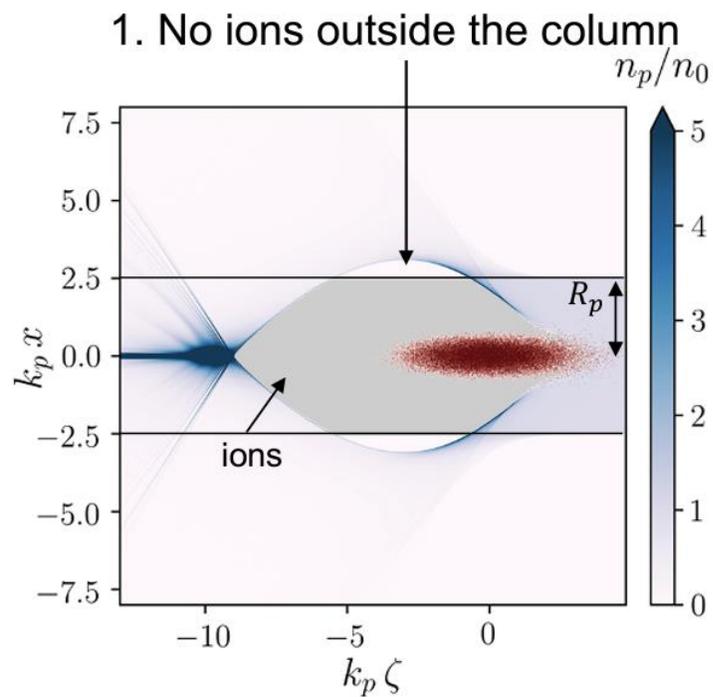


Focusing field for positrons

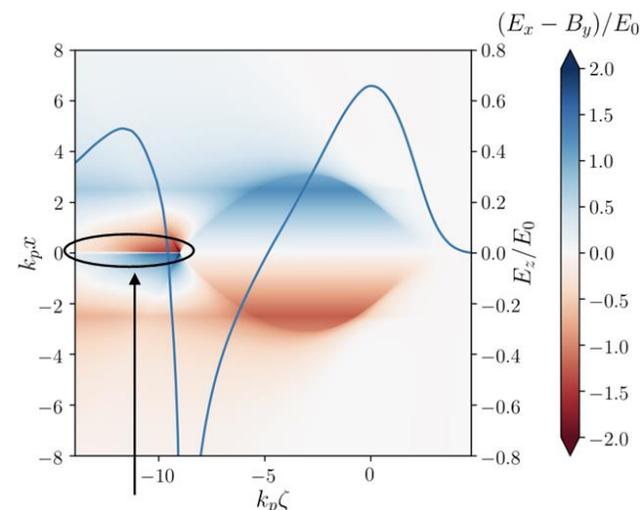


Positron acceleration

- There are many schemes for e+ acceleration – but currently, none can be tested experimentally.
- Most involve some sort of shaping or truncation of plasma to inhibit return flow of electrons from blowout.



3. Long, high-density electron filament



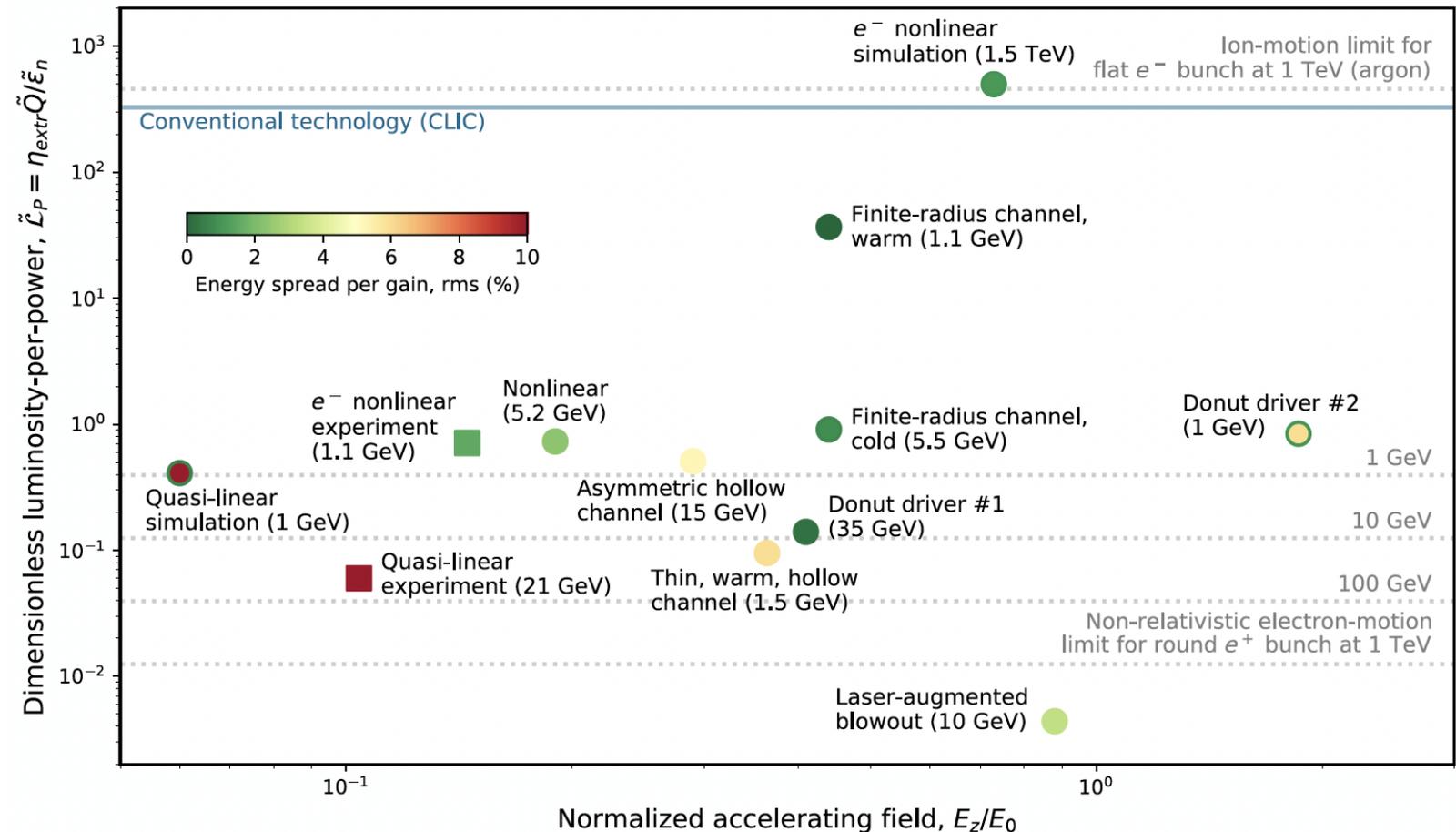
4. Accelerating and focusing fields for e+

$$0.5E_0 \approx 15 \text{ GV/m} \quad \text{at } n_0 = 1 \times 10^{17} \text{ cm}^{-3}$$

Positron Acceleration

- Even if one of these schemes proves to work reliably and reproducibly, they are generally not close to collider regime.

Recent review: [Cao, Lindström, Adli, Corde & Gessner, PRAB 27, 034801 \(2024\)](#)



Origin of 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

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

- We thought that the optimum (see later) for $E_{\text{cm}} = 250$ GeV is to pick $E_e = 500$ GeV, $E_p = 31$ GeV, which gives a boost in the electron direction of $\gamma \sim 2.13$.

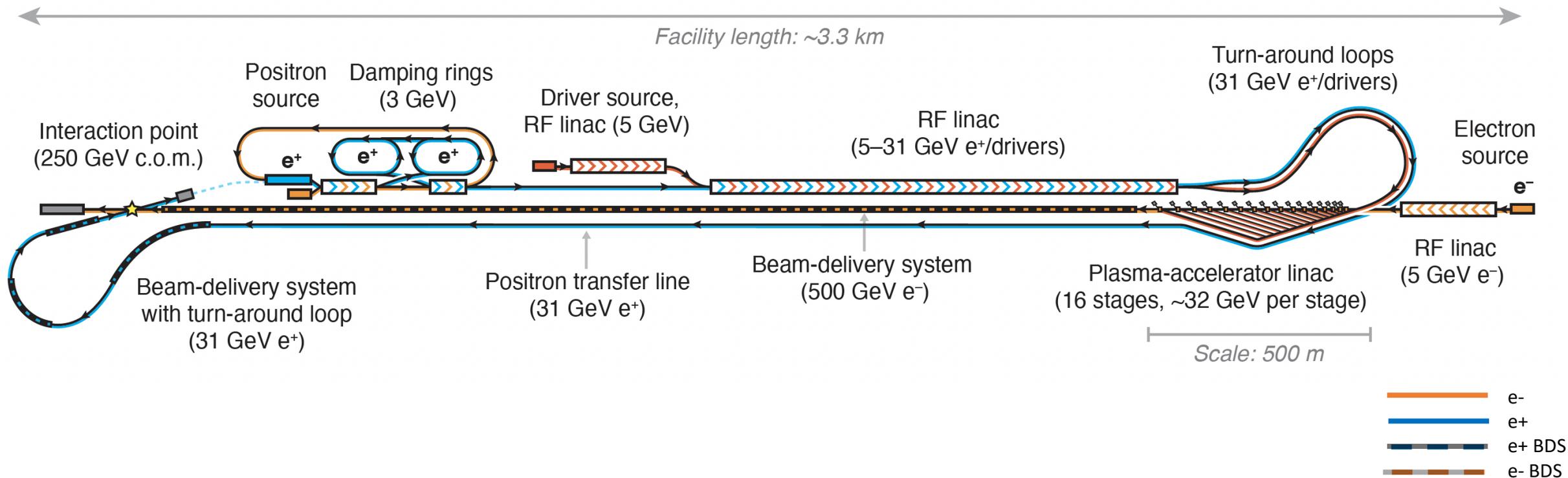
Power Efficiency

- Asymmetric machines less energy efficient than symmetric – energy lost “in accelerating the C.o.M.” For equal bunch charges => 2.5 times more power 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.
- $P/P_0 = (N_e E_e + N_p E_p) / (N \sqrt{s})$
- Optimum is to scale e^+ charge by $\sqrt{s} / (2E_p)$, i.e. factor ~ 4 .
- Producing so many e^+ problematic – compromise by scaling by factor 2 ($2 * e^+$, $1/2 * e^-$).
- **Reduces power 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 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 \Rightarrow normalized emittance can be 16 times higher for the same L \Rightarrow increased tolerances in PWFA arm.
- Beam-beam focusing effect on L must be simulated with Guinea Pig.

HALHF Layout



But hang on.....

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

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

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'	Nick Walker	Introduction
	10'	Nick Walker & Steffen Doebert	Linacs
	10'	Gudrid Moortgat-Pick	Positron source
	10'	Spencer Gessner	Beam delivery system
	20'	All	Open discussion
16:45	60'	Assessment of challenges for plasma systems	
	5'	Richard D’Arcy	Introduction
	15'	Erik Adli	High beam energy and quality
	5'	Kris Pöder	Spin polarisation
	15'	Richard D’Arcy	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

B. Fo



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

Problems with the original design

The laundry list



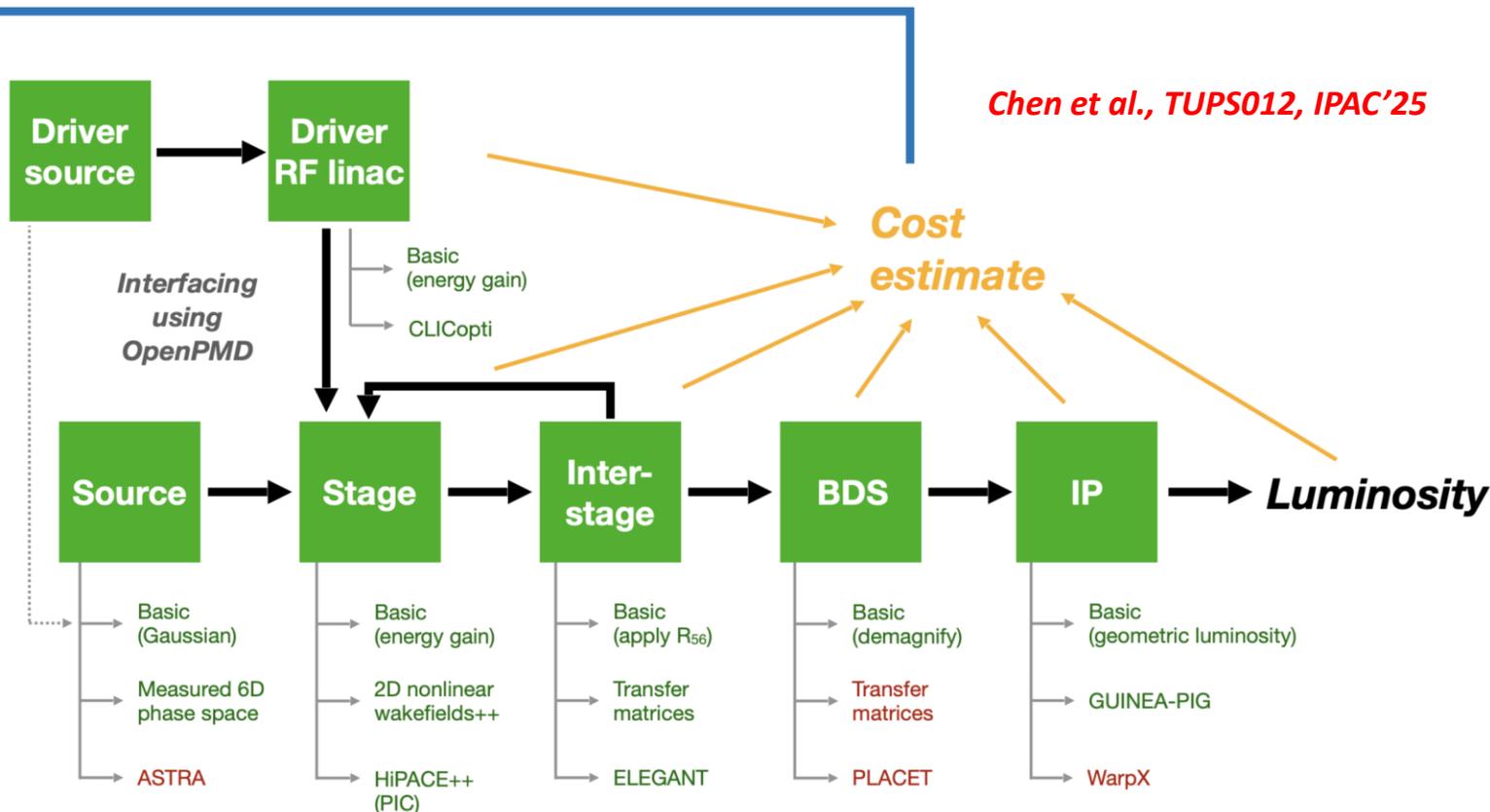
- > **Transverse instability, tolerances** are too tight.
- > **Beam ionisation** of the higher-order ionisation levels for argon (chosen to avoid ion motion).
- > **Cross-plane emittance mixing** (Diederichs *et al.*): large horizontal emittance leaks into vertical emittance.
- > **Plasma-cell cooling**: too much cooling required per length (~90 kW/m).
- > **Radiation reaction** at high energy: large induced energy spread (%-level).
- > **Bunch pattern** may not be compatible with PWFA: too much temperature increase? Effect on wakefields? Confinement?
- > Exceeded the **Oide limit** in the final focusing magnets.
- > **High-energy turn-arounds**: too much energy loss to synchrotron radiation.
- > The required **delay chicanes** are (transversely) large and costly. Strong bending magnets (SR is problematic).
- > **Combined RF accelerator** has too high gradient given its high power.
- > Required **driver bunch length** is too short: problematic beam loading in the RF linac (beam current too high).
- > The **instantaneous luminosity is too low**
- > **High positron bunch charge**: problematic for production and for collisions.
- > Need **polarised beams** for physics.
- > Unknown if we can **preserve spin polarization** of electrons in plasma stages and interstages.

Facility Optimisation

ABEL: The Adaptable Beginning-to-End Linac simulation framework

Bayesian optimisation
(adjust machine parameters)

Chen et al., TUPS012, IPAC'25



A start-to-end simulation framework, using OpenPMD

Adaptable implementations

- choose fidelity versus speed for each subsystem

Running other codes via wrappers (also submits HPC jobs etc.)

- HiPACE++, WakeT, ImpactX, GUINEAPIG, ELEGANT, CLICopti

Run simulations as experiments

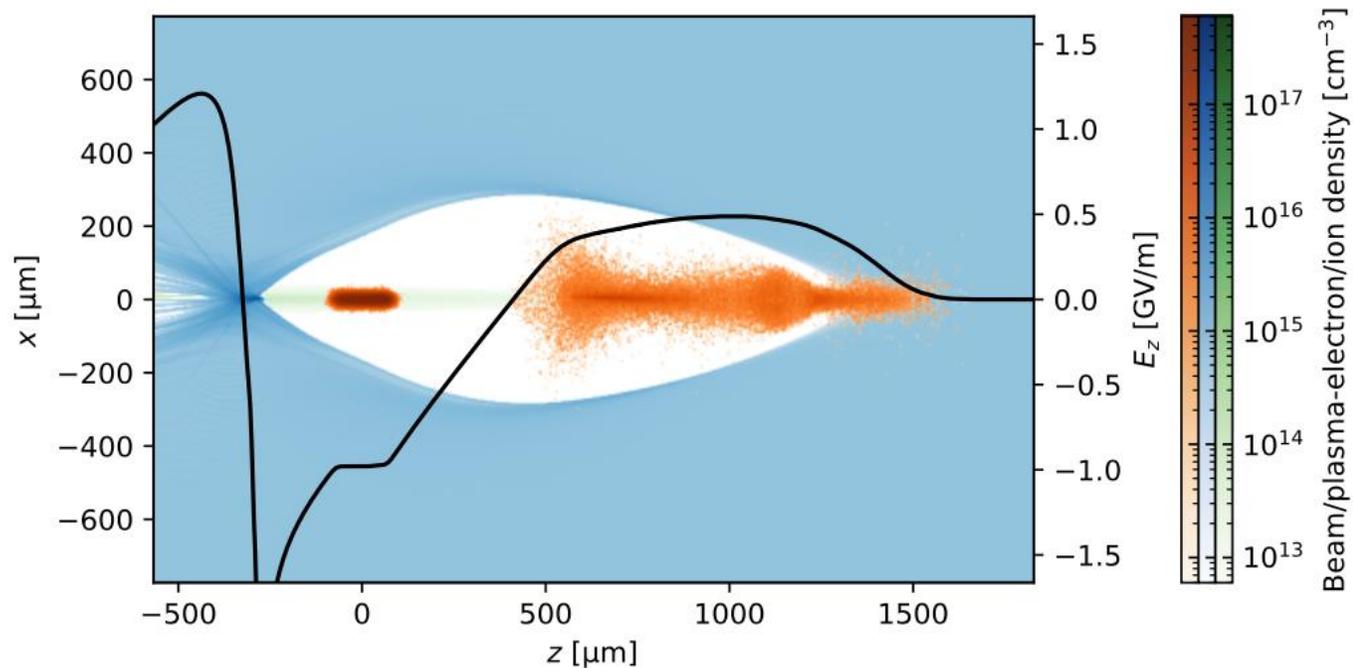
- run simulations with multiple shots, incl. random jitter
- perform automated scans (one-liner)
- perform parameter optimisations

“System code” (term borrowed from e.g. fusion)

- integrated cost modelling
- machine layouts

Now released as open source - Repository: <https://github.com/abel-framework/ABEL>

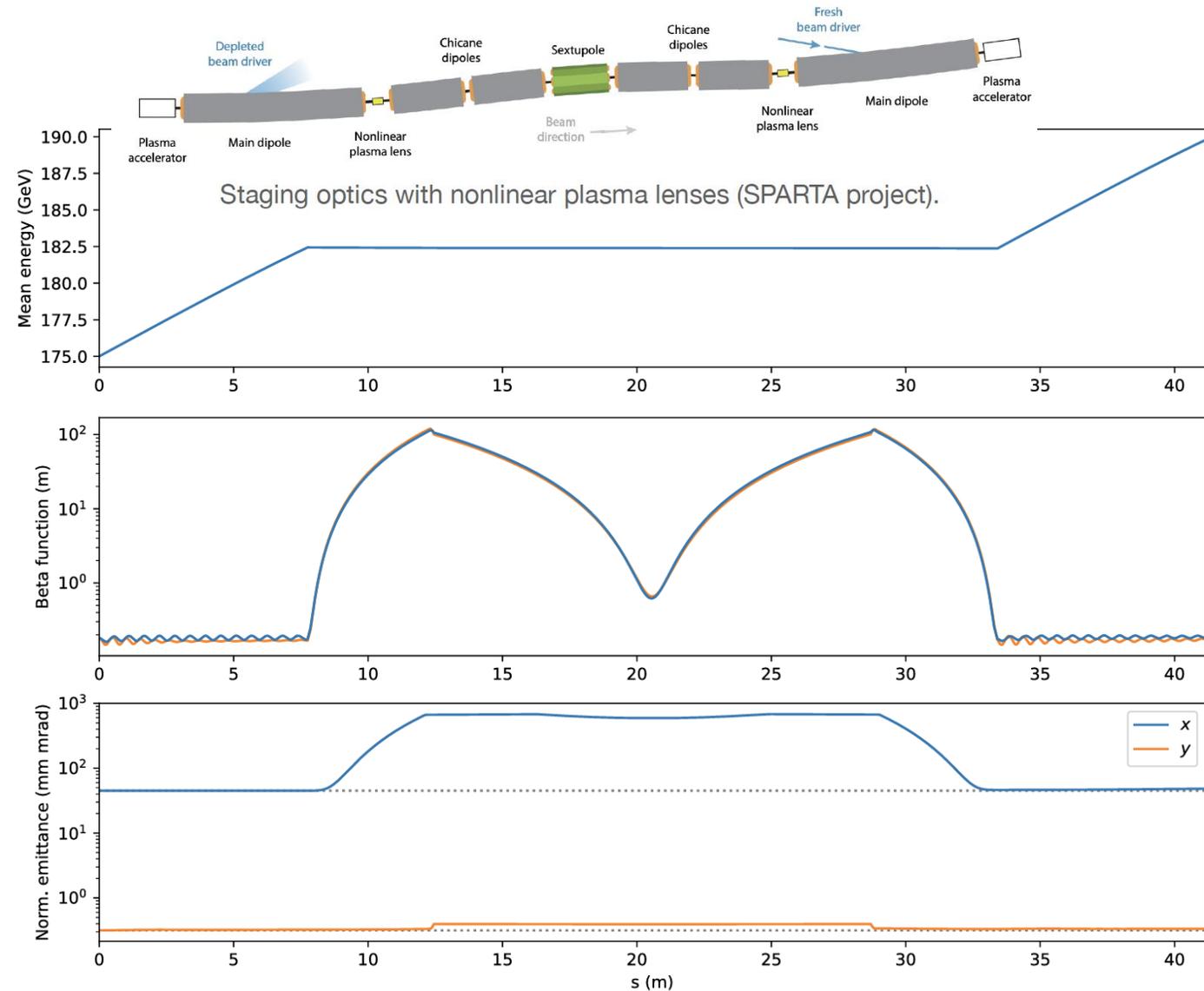
Blow-out simulation



PIC simulation with HiPACE++, He @ $6 \times 10^{14} \text{ cm}^{-3}$; driver and main beam (orange) 8 & 1.6 nC. Excess ion density on axis (green)

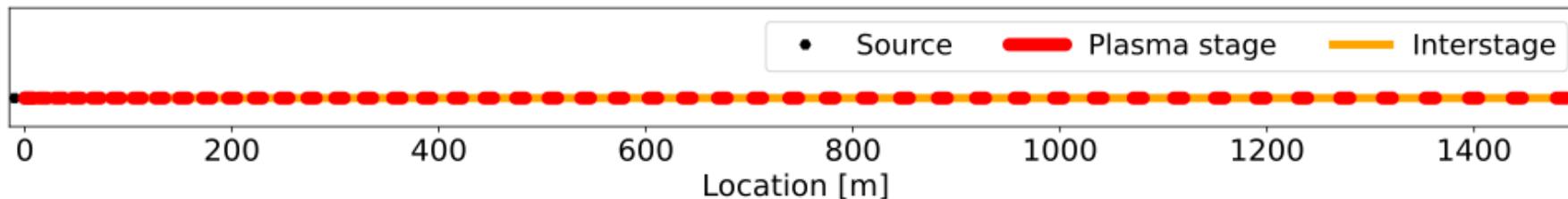
Two-stage simulation

- > **Self-consistent two-stage simulation (HiPACE++ and ImpactX) between 175–190 GeV**
 - > Corresponds to the middle stages of HALHF 250 GeV
 - > Preserves beam quality (in both PWFA and interstage)
- > *Achieves a deliverable (DEL 2.1) in the 2020 ESPPU roadmap* 
- > **Next:** Preparing for the full HALHF run (simulate all 48 stages)

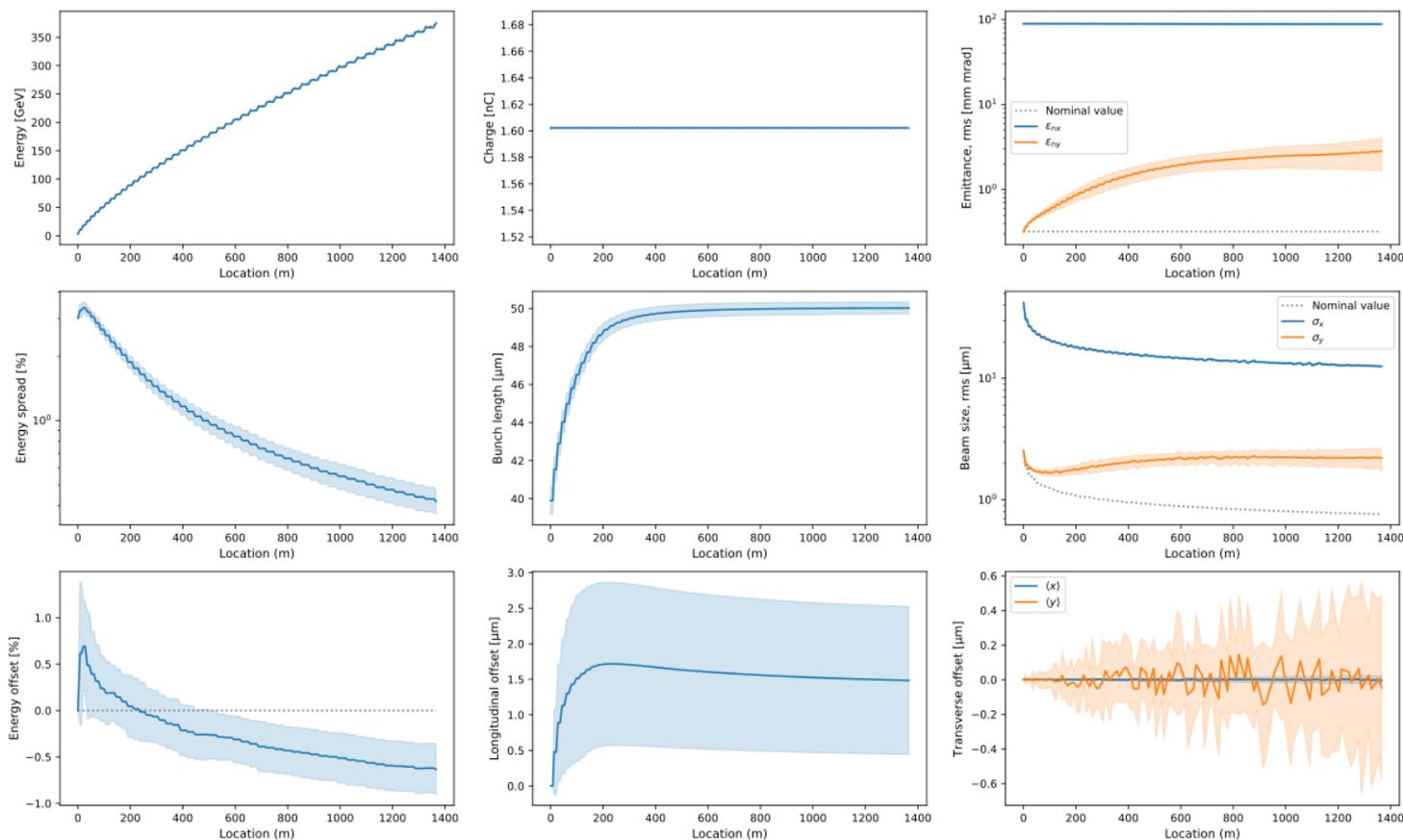


Towards Full Simulation

ABEL: The Adaptable Beginning-to-End Linac simulation framework



- > Flat-beam issue (Diederichs et al. 2024) suppressed with vertically flat driver
- > Ion motion suppresses transverse instability.
- > Longitudinal self-stabilization from compression between stages
- > Full simulation (minor simplifications only):
 - PIC simulation in stages (HiPACE++)
 - Particle tracking in interstages (ELEGANT)



Facility Optimisation

ABEL: The Adaptable Beginning-to-End Linac simulation framework

Defining a reasonable optimization metric

- > Developed a cost model (integrated into ABEL), accounting for the cost of all collider subsystems—scaled per length (and/or power) based on ILC/CLIC costs.
- > Defining a reasonable optimization metric is non-trivial:

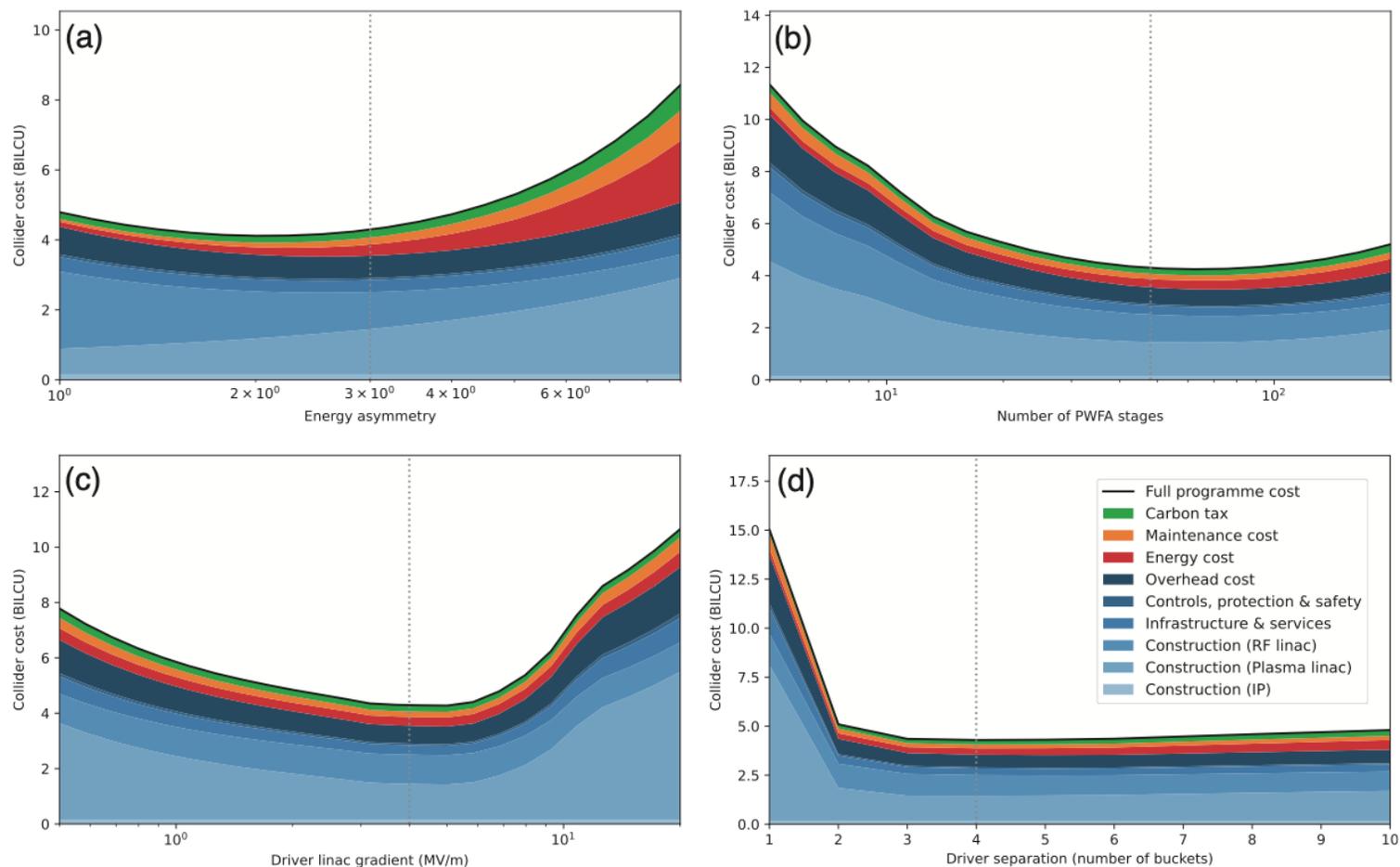
Full Programme Cost = Construction Cost (components and civil engineering)
+ Overheads (design, development, management, inspection, etc.)
+ Integrated Energy Cost (until integrated luminosity reached)
+ Maintenance Cost (over programme duration)
+ Carbon Shadow Cost (construction and operations emissions)

- > Using Bayesian optimization (and up to 12 key parameters) to find minimum cost—less than 100 iterations typically sufficient to find the global minimum.

Facility Optimisation

ABEL: The Adaptable Beginning-to-End Linac simulation framework

Bayesian optimization of cost – selected parameter variations



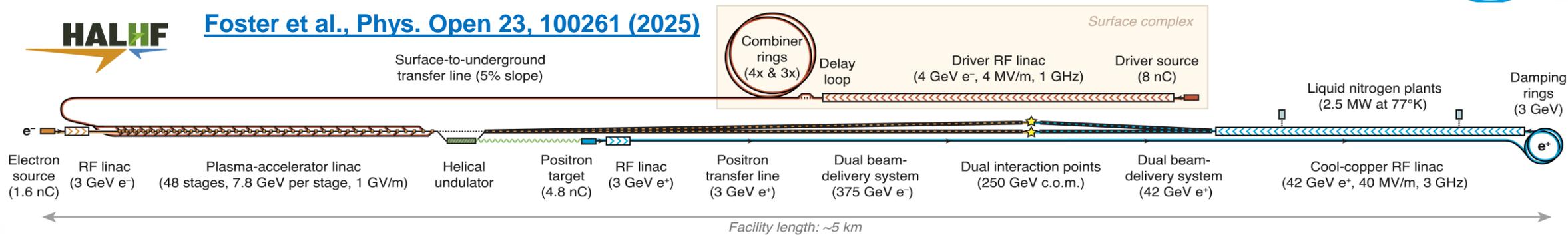
C. A. Lindstrøm et al. "Updated baseline design for HALHF: the hybrid, asymmetric, linear Higgs factory", Proc. IPAC'25, MOCD1

Facility Optimisation

**2nd HALHF
Workshop,
Erice,
3-8 October,
2024**



Foster et al., Phys. Open 23, 100261 (2025)

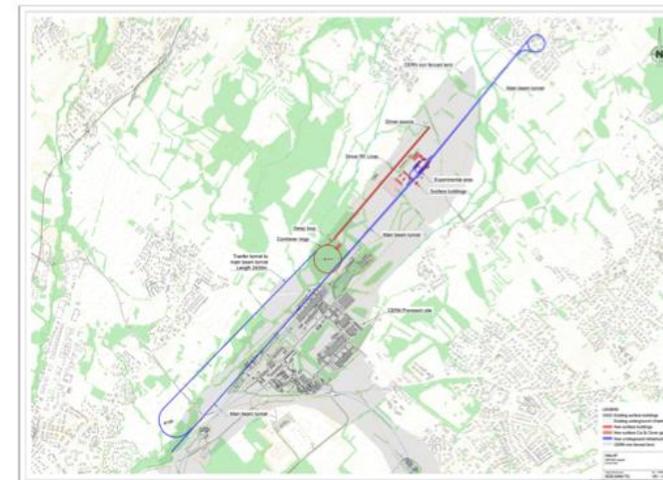
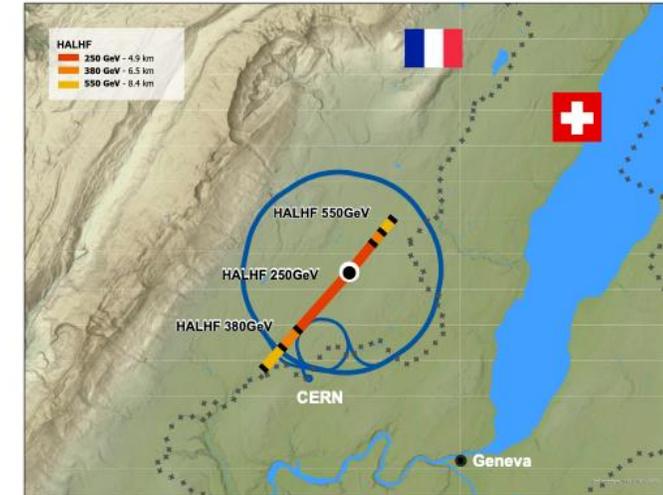
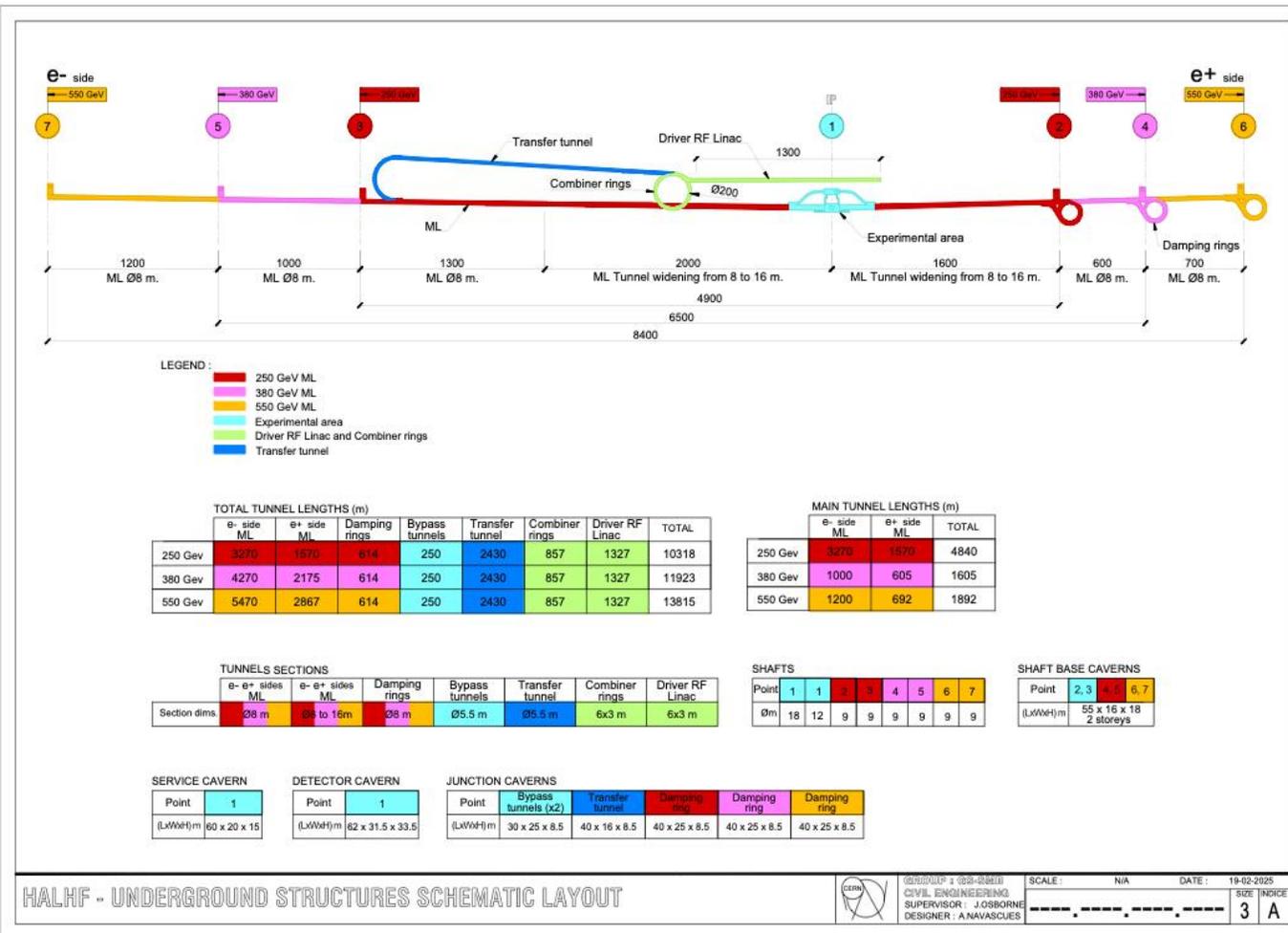


- > Two separate RF linacs (for more flexibility)
 - > L-band (1 GHz) CLIC-like drive-beam linac — 4 MV/m, 4 ns spacing, 8 nC
 - > S-band (3 GHz) cool-copper positron linac (warm-copper backup option) — 40 MV/m (25 MV/m), 16 ns spacing
- > Drive train compression (for reduced peak power in klystrons)
 - > Introduction of delay loop — 2x (requires phase coding)
 - > Introduce combiner rings — 12x compression of full train, 24x compression of driver stage-trains
- > Lower energy asymmetry — around 9x between e^+ and e^-
- > Positrons:
 - > Fewer positrons — 3×10^{10} (4.8 nC)
 - > Polarized positron source (helical undulator) — at the end of the PWFA linac
- > PWFA stages:
 - > More stages: 48 stages
 - > Lower gradient — 1 GV/m
 - > Lower density — $6 \times 10^{14} \text{ cm}^{-3}$
 - > Higher driver charge — 5×10^{10} (8 nC)
 - > Higher transformer ratio — $T=2$
- > Higher collision rate — 160 bunches per burst @ 100 Hz = 16 kHz (to have similar luminosity to ILC)

HALHF 2.0 – CERN site study

Prepared for the ESPP input (<https://arxiv.org/abs/2503.19880>)

E. Adli et al. “HALHF: a hybrid, asymmetric, linear Higgs factory using plasma- and RF-based acceleration. Backup Document”, arXiv:2503.23489



Cost estimates for HALHF 2.0

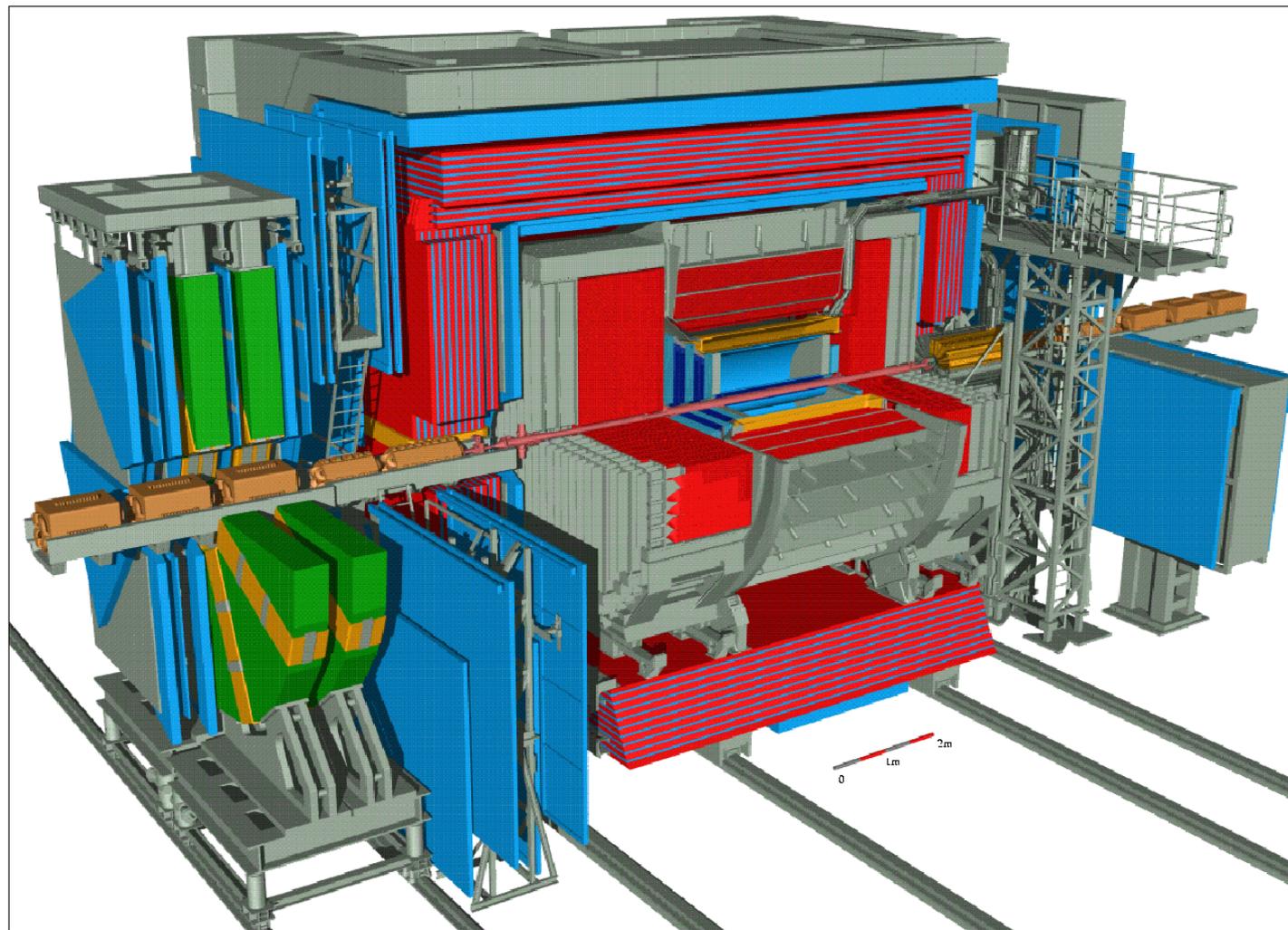
E. Adli et al. "HALHF: a hybrid, asymmetric, linear Higgs factory using plasma- and RF-based acceleration", [arXiv:2503.19880](https://arxiv.org/abs/2503.19880)

Based scaling from ILC and CLIC

- > Driver RF linac is a major cost driver for the machine (~30%; 50% incl. e⁺ linac)
 - > Drivers: ~22 CHF/watt beam power
 - > Positrons: ~167 CHF/watt beam power
- > PWFA linac is not a cost driver (~7%)
 - > Driver distribution is the cost driver
- > BDS and IP (~13%) adds
- > Civil engineering adds ~25% to the machine cost, other overheads ~30%
 - > Cooling and ventilation is expensive (~3.6 CHF/watt wall-plug power)

Domain	Sub-domain	Cost [MILCU]		
		250 GeV	380 GeV	550 GeV
Main-beam production	Electron source (photocathode, polarized)	82	82	82
	Electron injector linac	22	22	22
	Positron source (helical undulator, polarized)	178	178	178
	Positron injector linac	32	32	32
	Positron transport	55	74	96
	Positron damping rings (2x)	200	200	200
Drive-beam production	Electron source	10	10	10
	Driver linac modules	113	173	254
	Driver linac RF	325	501	731
	Frequency multiplication (combiner rings)	127	127	127
	Driver transport (surface-to-underground)	24	25	26
Electron linac (PWFA)	Plasma modules	17	26	38
	Interstage transport	30	37	44
	Driver delay chicanes	90	120	155
	Driver beam dumps	11	17	25
Positron linac (cool-copper RF)	Cool-copper linac modules	113	176	259
	Cool-copper linac RF	298	465	683
	LN ₂ reliquification plants	34	53	78
Beam delivery and post collision lines (dual IPs)	Electron beam delivery systems (2x)	158	194	234
	Positron beam delivery systems (2x)	53	65	78
	Final focus, experimental area	20	20	20
	Post collision lines/dumps	45	64	88
Civil engineering	Surface driver and complex	63	92	130
	Surface-to-underground tunnel	31	31	31
	Electron arm tunnel	44	59	75
	Positron arm and damping ring tunnels	54	77	106
	Beam-delivery systems	164	201	243
	Interaction region	154	154	154
Infrastructure and services	Electrical distribution	104	125	150
	Survey and alignment	80	96	116
	Cooling and ventilation	302	439	622
	Transport / installation	24	29	35
Machine control, protection and safety systems	Safety systems	30	36	43
	Machine control infrastructure	60	72	87
	Machine protection	6	7	9
	Access safety & control system	9	11	14
Total (in 2012 MILCU)		3162	4090	5275
Total (in 2024 Swiss francs)		3.8 BCHF	4.9 BCHF	6.3 BCHF

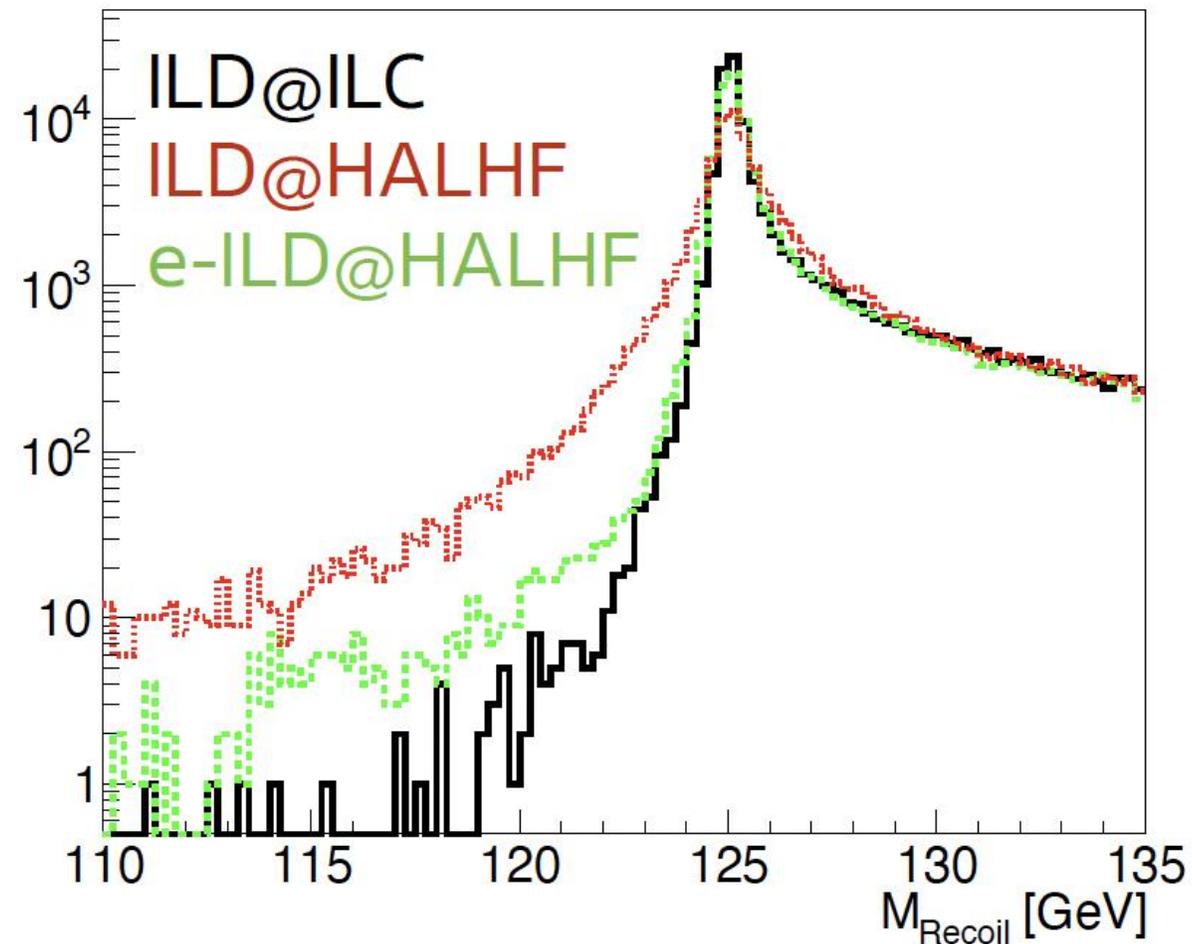
- Boost is smaller than HERA - HERA detectors very similar to those at symmetric machines.
- Also H & Z heavy, so anyway more homogeneous.
- Measurement of L via Bhabha ($e^+e^- \rightarrow e^+e^-$) - rate reduced by $1/(\theta_\gamma)^2$ & e^+ scattered into barrel – but not a problem. Singles rate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



ZEUS (HERA) 

Software :SDRC-IDEAS level V1.1
Performed by : Carsten Hartmann
Status : October 1993

- Simulation by M. Berggren, A. Laudrain (DESY) – extend ILC Barrel as proxy for forward detector;
- “Proper” simulation needed and under discussion.



Source: A. Laudrain, talk at EPS-HEP Conference (2023)

Preparation for pre-CDR

G. Global Issues supergroup		
G1. Global optimization and coordination		R. D'Arcy, B. Foster, C. Lindstrøm
G2. Global self-consistent start-to-end simulation		E. Adli, C. Lindstrøm, B. Chen, M. Thévenet
P. PWFA supergroup		
P1. PWFA linac		E. Adli, C. Lindstrøm, K. Pöder
P2. Plasma heating and cooling		R. D'Arcy, J. Wood
P3. PWFA driver distribution & delays, combiner rings		D. Kalvik, C. Lindstrøm
P4. Driver dumping and radiation safety		S. Boogert, S. Bohlen
C. Other Accelerator Systems supergroup		
C1. RF driver linac		K. Sjobak
C2. BDS and collimation		R.T. Garcia, A. Seryi
C3. Damping rings		Dou Wang
C4. Polarized positron source		Gudrid Moortgat-Pick
C5. Polarized electron source and injector		Xiaoping Li
C6. Positron RF linac		
C7. Structure acceleration & alternatives to klystrons		Xueying Lu
C8. Civil engineering and sustainability		E. Mactavish, J. Osborne
D. Physics and detector supergroup		
D1. Physics, asymmetric detector, IP beam dynamics		J. List, M. Wing

- Despite ~ 0 project funding (only a few FTEs from JAI general programme, DESY & CERN), HALHF is making rapid progress;
- New baseline & costing carried out;
- HALHF input to European Strategy:
 - 10pager:** <https://arxiv.org/abs/2503.19880>
 - Backup:** <https://arxiv.org/abs/2503.23489>
- ~ 15 year R&D programme before approval
- Regular monthly HALHF meetings;
- Longer-term goal: pre-CDR this year; & funding to start R&D programme;
- Contribute to 10 TeV design

The march of progress

From *then to now* – a summary (<https://arxiv.org/abs/2509.07910>)

Evolution of the plasma-based collider concept over the last decade (towards HALHF)

> What has changed since Snowmass 2013?

- > The open challenge of **positron acceleration in plasma** has been sidestepped (acceleration in **C³-like linac** instead)
- > Established **CLIC drive-beam technology** has been adopted (with an associated reduction in beam energy)
- > The **transverse beam-break-up** (BBU) instability has been taken in to account and partially mitigated (with e.g. ion motion effects)
- > Emittance-preserving **interstage optic schemes** have been devised
- > **Plasma recovery** and **plasma-source cooling** have been taken in to account
- > **Integrated codes** have leveraged **developments in PIC** (GPU operation, mesh refinement, etc.) to perform full plasma linac simulations
- > Similarities with ILC and CLIC sub-systems has enabled the **translation of costs from more robust collider concepts**
- > A **global system optimisation for cost** has been applied

Progress

RF Tech

R&D

New Tools

Costing

NB – many of these issues, particularly transverse tolerances and instability mitigation are still work in progress!

Path to construction

R&D element	Start year	Duration (years)	Personnel (FTE years)	Capital (MCHF)
<i>Phase 1: Basic R&D and integrated collider design</i>				
Plasma accelerator R&D:				
Single-stage quality preservation at high efficiency demonstration (ongoing)	0	5	90	13
Basic staging and beam-quality R&D:				
Self-consistent PWFA staging simulations (incl. spin polarization)	0	3	15	2
Demonstrating achromatic staging optics (nonlinear plasma lens)	0	3	5	3
Quality-preserving stage-to-stage transport experiment	3	2	10	5
Basic plasma heating and cooling R&D				
Self-consistent long-term plasma evolution simulations	0	3	10	1
Cooled plasma-cell development	0	5	30	5
High-peak-power plasma evolution experiment (in existing PWFA facilities)	0	5	10	2
Collider design (toward CDR):				
Polarized e^+ source R&D	0	5	16	3
Positron linac design (e.g., cool copper)	0	5	10	10
Drive-beam complex design (linac, combiner rings, etc.)	0	5	20	7
Beam-delivery system design (incl. double IP)	0	5	10	1
Asymmetric physics and detector design (Not included in accelerator design)				
<i>Phase 2: Key demonstrations</i>				
Plasma demonstrations:				
Staging and stability demonstrator (new dedicated facility; SFQED application)	5	5	25	60
High-average-power plasma-cell demonstration (upgrading an existing facility)	5	5	20	20
Single-stage polarization preservation experiment	7	3	15	20
Self-consistent full-train start-to-end simulations	5	5	5	1
Other systems demonstrations:				
Cool-copper RF linac demonstrator (parallel development to HALHF)				
Polarized positron source demonstrator (parallel development to HALHF)				
<i>Phase 3: HALHF (all in one) demonstrator</i>				
Upgrade of staging facility with high-power plasma cells and RF	10	5	20	25
Upgrade to include increased beam quality	12	3	20	25
Upgrade to include spin polarized source	13	2	10	10
Total		15 yrs	341 FTE yrs	213 MCHF

Table 3: HALHF R&D Milestones and required resources to produce a Technical Design Report (TDR). (This table is reproduced from Table 2 in the Comprehensive Summary [1].)

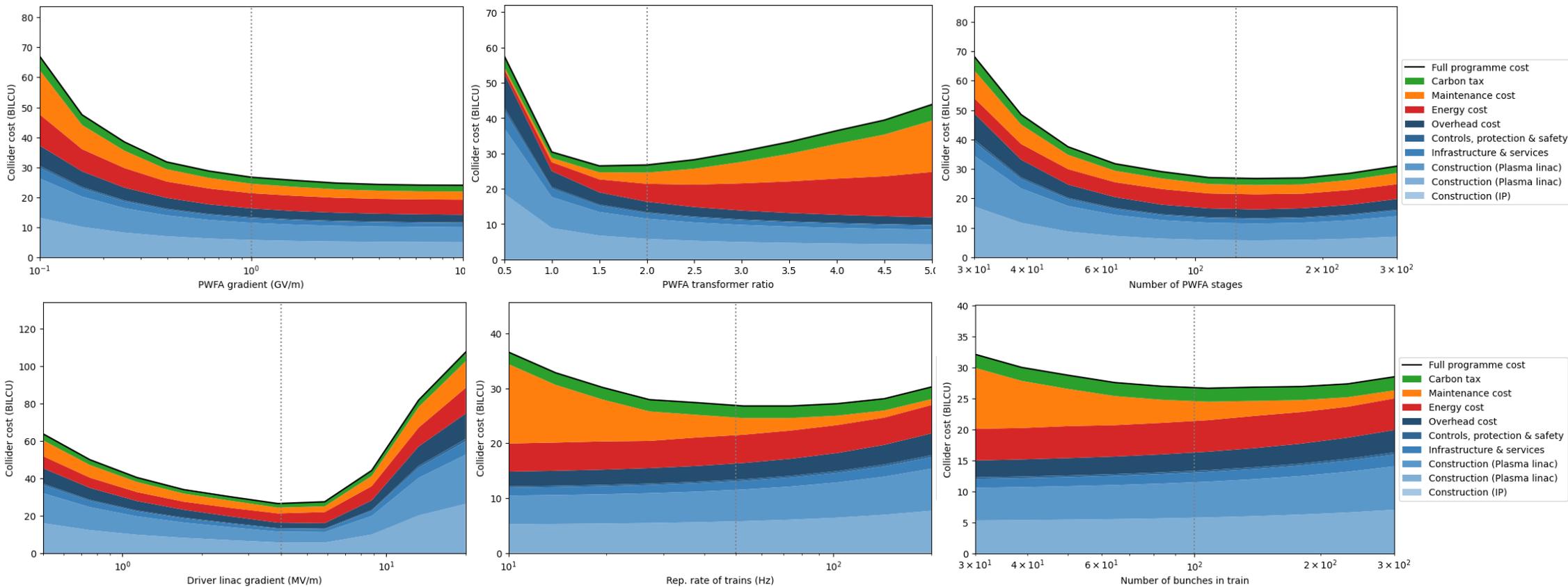
10 TeV Wakefield Collider

Challenges

- Inefficient acceleration of positrons in plasma
 - **Proposed solution:** Take advantage of large VBF cross-section and utilize gamma-gamma or e^-e^- collisions instead.
- Extreme beamstrahlung at high collision energies and beam densities
 - **Proposed solution:** 1) Collide ultrashort bunches to mitigate beamstrahlung and 2) Embrace the broad luminosity spectrum so long as significant fraction of the colliding particles are close to 10 TeV CM.
- Detector design and background modeling for high energy collisions
 - **Proposed solution:** Development of new Particle-in-Cell codes, benchmarked against GUINEA-PIG and CAIN, to accurately model backgrounds for high-energy gamma-gamma, e^-e^- , and e^-e^+ collisions.
- 10 TeV Design Study sign up @ https://docs.google.com/forms/d/e/1FAIpQLScffLXDxF_8-TUYaWLznL7jAWUGfYOTEzBu4YrOnr8nRS-JQw/viewform

Simplified 10 TeV $\gamma\text{-}\gamma$ collider with “two HALHFs”

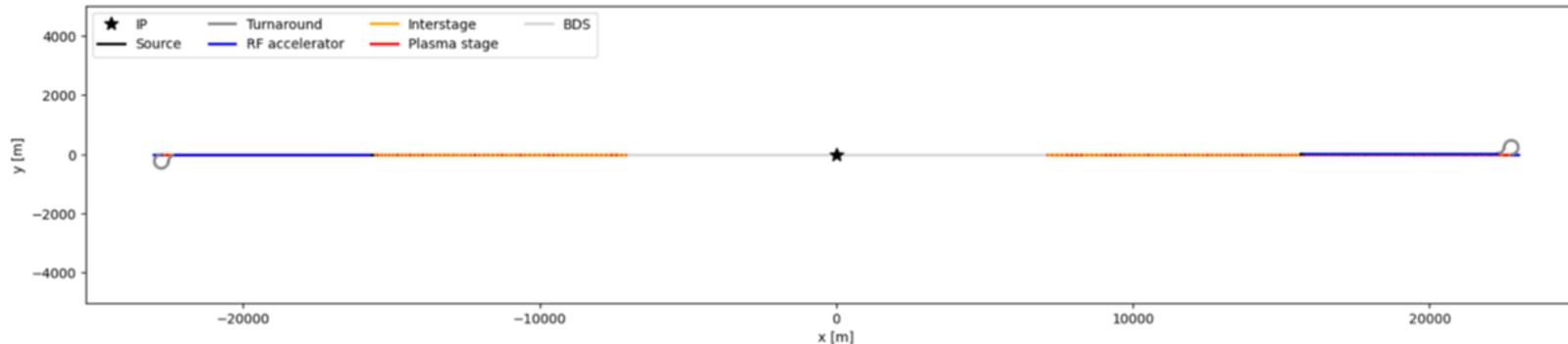
HALHF-like, with 125 stages/arm and 20 GeV drivers, 100 bunches @ 50 Hz, 1x1 mm mrad, 1.6 nC, 45% Compton conversion



10 TeV Wakefield Collider

- Simplified 10 TeV γ - γ collider with “two HALHFs”

HALHF-like, with 125 stages/arm and 20 GeV drivers, 100 bunches @ 50 Hz, 1x1 mm mrad, 1.6 nC, 45% Compton conversion



- > Collider length: ~46 km
- > Collider power: ~500 MW
- > Runtime: ~34 years (10/ab of data)
- > Collider construction cost: ~14 BILCU (~16 BCHF)
- > Full programme cost: ~27 BILCU (~32 BCHF)

```

-- COSTS -----
-- Construction: 13664 MILCU
-- Plasma linac: 5727 MILCU (2x = 11454 MILCU)
-- Polarized electron source: 82 MILCU
-- RF injector: 37 MILCU
-- Instrumented beamline (25%): 1 MILCU
-- RF structures (74x): 21 MILCU
-- Klystrons (74x, 8 MW peak, 42 kW avg): 14 MILCU
-- Driver complex: 2478 MILCU
-- Source: 10 MILCU
-- Driver RF linac: 2096 MILCU
-- Instrumented beamline (25%): 25 MILCU
-- RF structures (2159x): 571 MILCU
-- Klystrons (2160x, 18 MW peak, 90 kW avg): 1500 MILCU
-- Turnaround: 67 MILCU
-- Civil construction: 305 MILCU
-- Driver source (cut & cover + surface building): 1 MILCU
-- Driver RF linac (cut & cover + surface building): 285 MILCU
-- TurnaroundBasic (small tunnel): 19 MILCU
-- Plasma stages (125x): 231 MILCU
-- Interstages: 430 MILCU
-- Driver dumps (125x, 25 MW total): 60 MILCU
-- Driver delay chicanes (left+right): 1265 MILCU
-- BDS (1x): 288 MILCU
-- Civil construction: 857 MILCU
-- SourceBasic: 0 MILCU
-- RF injector: 9 MILCU
-- BDS: 265 MILCU
-- Plasma stages (125x, widened 3x): 186 MILCU
-- Interstages (124x, widened 3x): 396 MILCU
-- Interaction point (1x): 77 MILCU
-- Experimental area: 20 MILCU
-- Post-collision beamlines: 268 MILCU
-- Plasma linac beamline: 38 MILCU
-- Plasma linac beamline: 38 MILCU
-- Plasma linac dump: 96 MILCU
-- Plasma linac dump: 96 MILCU
-- Infrastructure & services: 1560 MILCU
-- Controls, protection & safety: 285 MILCU
-- Overheads: 2943 MILCU
-- Design/development: 1338 MILCU
-- Management/inspection: 1605 MILCU
-- Energy (492 MW, 10/ab, 33.8 yrs): 5099 MILCU
-- Maintenance: 3164 MILCU
-- Carbon tax (2730 kton CO2e): 2184 MILCU
-----
-- Total: 27.05 BILCU
  
```

† The HALHF Collaboration: Erik Adli¹, Joshua Appleby², Timothy L. Barklow³, Maria Enrica Biagini⁴, Jonas Björklund Svensson⁵, Mikael Berggren⁶, Simona Bettoni⁷, Stewart Boogert⁸, Philip Burrows², Allen Caldwell⁹, Jian Bin Ben Chen¹, Vera Cilento^{2,10}, Laura Corner¹¹, Richard D’Arcy², Steffen Doebert¹⁰, Wang Dou¹², Pierre Drobniak¹, Calvin Dyson¹³, Sinead Farrington¹⁴, John Farmer⁹, Angeles Faus-Golfe¹⁵, Manuel Formela⁶, Arianne Formenti¹⁶, Louis Forrester¹³, Brian Foster^{2,6}, Jie Gao¹², Spencer Gessner³, Niclas Hamann⁶, Alexander Harrison², Mark J. Hogan³, Eir Eline Hørlyk¹, Maryam Huck⁶, Daniel Kalvik¹, Antoine Laudrain⁶, Reme Lehe¹⁶, Wim Leemans⁶, Carl A. Lindstrøm¹, Benno List⁶, Jenny List⁶, Xueying Lu¹⁷, Edward Mactavish¹⁰, Vasyl Maslov⁶, Emilio Nanni³, John Osborne¹⁰, Jens Osterhoff¹⁶, Felipe Peña^{18,1}, Gudrid Moortgat Pick^{19,6}, Kristjan Pöder⁶, Jürgen Reuter⁶, Dmitrii Samoilenko⁶, Nela Sedlackova¹³, Andrei Seryi²⁰, Kyrre Sjobak¹, Terry Sloan²¹, Rogelio Tomas Garcia¹⁰, Maxim Titov²², Malte Trautwein¹⁹, Steinar Stapnes¹⁰, Maxence Thévenet⁶, Nicholas J. Walker⁶, Marc Wenskat⁶, Matthew Wing^{23,6}, Jonathan Wood⁶.

(April 2025)

¹ Department of Physics, University of Oslo, 0316 Oslo, Norway

² John Adams Institute for Accelerator Science at University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK

³ SLAC National Accelerator Laboratory, 2575 Sand Hill Road, CA 94025, Menlo Park, USA

⁴ Laboratori Nazionali di Frascati, INFN, Via Enrico Fermi, 54, 00044 Frascati RM, Italy

⁵ Department of Physics, Lund University, Box 118, 221 00 Lund, Sweden

⁶ DESY, Notkestrasse 85, 22607, Hamburg, Germany

⁷ Paul Scherrer Institute, Forschungsstrasse 111, 5232 Villigen, Switzerland

⁸ Cockcroft Institute, Daresbury Laboratory, STFC, Keckwick Lane, Daresbury, WA4 4AD, Warrington, UK

⁹ Max Planck Institut für Physik, Boltzmannstrasse 8, 85748 Garching/Munich, Germany

¹⁰ CERN, CH-1211 Geneva 23, Switzerland

¹¹ Cockcroft Institute at University of Liverpool, School of Engineering, The Quadrangle, Brownlow Hill, Liverpool L69 3GH, UK

¹² Institute of High Energy Physics, Chinese Academy of Sciences, 9 Yuquan Rd, Shi Jing Shan Qu, Bei Jing Shi, 100039, China.

¹³ John Adams Institute for Accelerator Science at Department of Physics, Imperial College London, Prince Consort Road, South Kensington, London SW7 2BW, UK

¹⁴ Rutherford Appleton Laboratory, STFC, Harwell Campus, OX11 0QX, Didcot, UK

¹⁵ Laboratoire de Physique des 2 Infinis Irène Joliot-Curie, IJCLab, Orsay, Bât. 100 et 200, 15 rue Georges Clémenceau, F-91405 Orsay, France

¹⁶ Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, CA 94720, USA

¹⁷ Argonne National Laboratory, 9700 S Cass Avenue, IL60439, Lemont, USA

¹⁸ Ludwig-Maximilians-Universität München, Geschwister-Scholl-Platz 1, 80539 München, Germany

¹⁹ II. Institute of Theoretical Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

²⁰ Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, VA23606, Newport News, USA

²¹ University of Lancaster, Bailrigg, Lancaster LA1 4YW, UK

²² CEA-IRFU, Bât. 141 CEA - Saclay, 91191 Gif-sur-Yvette, France

²³ Department of Physics & Astronomy, University College London, Gower St, London WC1E 6BT, UK

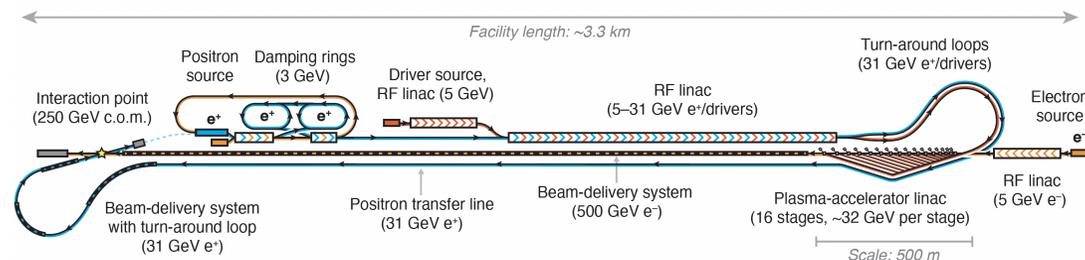
- Despite ~ 0 funding, HALHF is making rapid progress;
- New baseline & costing carried out;
- HALHF input to European Strategy: **10pager**: <https://arxiv.org/abs/2503.19880>

Backup: <https://arxiv.org/abs/2503.23489> - ~ 15 year R&D programme before approval

- Regular monthly HALHF accelerator meetings;
- Medium-term goal: pre-CDR in 2026 & funding to start R&D programme;
- Contribute to 10 TeV design.
 - **PLEASE JOIN US:** <https://adams-institute.ac.uk/halhf>

Backup slides

Running Costs



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

Backup slide — HALHF 2.0 parameter table (part 1)

<i>Machine parameters</i>	<i>Unit</i>	<i>Value (250 GeV)</i>		<i>Value (380 GeV)</i>		<i>Value (550 GeV)</i>	
Centre-of-mass energy	GeV	250		380		550	
Centre-of-mass boost		1.67		1.67		1.67	
Bunches per train		160		160		160	
Train repetition rate	Hz	100		100		100	
Average collision rate	kHz	16		16		16	
Luminosity	$\text{cm}^{-2} \text{s}^{-1}$	$1.2 \rightarrow 10^{34}$		$1.7 \rightarrow 10^{34}$		$2.5 \rightarrow 10^{34}$	
Luminosity fraction in top 1%		63%		53%		46%	
Quantum parameter (!)		0.9		1.6		2.8	
Estimated total power usage	MW	106		154		218	
Total site length	km	4.9		6.5		8.4	
<i>Colliding-beam parameters</i>							
Beam energy	GeV	e^- 375		e^+ 41.7		e^- 825	
Bunch population	10^{10}	1		3		3	
Bunch length in linacs (rms)	μm	40		150		40	
Bunch length at IP (rms)	μm			150		150	
Energy spread (rms)	%	0.15		0.15		0.15	
Horizontal emittance (norm.)	μm	90		10		90	
Vertical emittance (norm.)	μm	0.32		0.035		0.32	
IP horizontal beta function	mm	3.3		3.3		3.3	
IP vertical beta function	mm	0.1		0.1		0.1	
IP horizontal beam size (rms)	nm	636		519		429	
IP vertical beam size (rms)	nm	6.6		5.2		4.4	
Average beam power delivered	MW	9.6		3.2		14.6	
Bunch separation	ns	16		16		16	
Average beam current	μA	26		77		26	
<i>Positron cool-copper RF linac parameters (S-band)</i>							
Average cavity gradient	MV/m	40		40		40	
Average gradient	MV/m	36		36		36	
Wall-plug-to-beam efficiency	%	11		11		11	
RF power	MW	11.7		17.8		25.8	
Cooling power	MW	17.9		27.3		39.5	
Total power	MW	29.6		45.1		65.3	
Klystron peak power	MW	67		67		67	
Number of klystrons		321		452		678	
RF frequency	GHz	3		3		3	
Operating Temperature	K	77		77		77	
Length (after damping ring, starting at 3 GeV)	km	1.1		1.7		2.5	

Backup slide — HALHF 2.0 parameter table (part 2)

<i>Driver linac RF parameters (L-band)</i>				
Average cavity gradient	MV/m	4	4	4
Average gradient	MV/m	3	3	3
Wall-plug-to-beam efficiency	%	55	55	55
RF power usage	MW	42.9	66.0	96.4
Klystron peak power	MW	21	21	21
Number of klystrons		409	630	919
RF frequency	GHz	1	1	1
Length	km	1.3	1.9	2.8
<i>Combiner Ring parameters</i>				
Delay loop length	m	1.5	1.5	1.5
CR1 diameter	m	244	244	244
CR2 diameter	m	244	244	244
<i>PWFA linac and drive-beam parameters</i>				
Number of stages		48	48	48
Plasma density	cm ⁻³	6 → 10 ¹⁴	6 → 10 ¹⁴	6 → 10 ¹⁴
In-plasma accel. gradient	GV/m	1	1	1
Av. gradient (incl. optics)	GV/m	0.33	0.38	0.43
Transformer ratio		2	2	2
Length per stage	m	7.8	11.8	17.1
Energy gain per stage	GeV	7.8	11.8	17.1
Initial injection energy	GeV	3	3	3
Driver energy	GeV	4	5.9	8.6
Driver bunch population	10 ¹⁰	5.0	5.0	5.0
Driver bunch length (rms)	μm	253	253	253
Driver average beam power	MW	23.8	36.2	52.6
Driver bunch separation	ns	4	4	4
Driver-to-wake efficiency	%	80	80	80
Wake-to-beam efficiency	%	50	50	50
Driver-to-beam efficiency	%	40	40	40
Wall plug-to-beam efficiency	%	22	22	22
Cooling req. per stage length	kW/m	38.4	38.4	38.4
Length	km	1.1	1.5	1.9

Backup slide — Cost model table (part 1)

Cost element (per length)	Cost/length (kILCU/m)	Length (m)			Ref.	Comment
		250 GeV	380 GeV	550 GeV		
Accelerating structures	115.00	2,052	3,102	4,474	CLIC	Assumed same for L- & S-band.
Damping rings	260.00	767	767	767	CLIC	Two rings in one tunnel.
Combiner ring	79.00	1,535	1,535	1,535	CLIC	Two rings in one tunnel.
Beam-delivery system	40.44	5,196	6,406	7,707	ILC	Doubled for dual IP
Post-BDS beamline	40.44	346	427	514	ILC	Costed as BDS.
Turn-arounds	40.44	213	213	213	ILC	Costed as BDS
Instrumented beamline	15.40	437	666	966	ILC	In between acc. structures.
Transfer line	15.40	6,087	7,294	8,732	ILC	Costed as instrum. beamline. Driver and e ⁺ transfer lines.
Plasma cells	46.20	375	570	825		3→instrumented beamline
Interstage optics	40.44	738	910	1095		Costed as BDS
Driver-distribution system (both sides of plasma linac)	40.44	2,226	2,960	3,840		Costed as BDS. One on each side of the plasma linac.
Tunnel (4.0 m inner diam.)	11.89	2,713	2,713	2,713	CLIC	Outer diameter 5.1 m. Surface-to-underground and turnaround.
Tunnel (5.6 m inner diam.)	20.19	560	560	560	CLIC	Outer diameter 6.7 m. Damping ring and e ⁺ source and injector.
Tunnel (8.0 m inner diam.)	37.15	4,951	6,525	8,403	CLIC	Outer diameter 9.1 m. e ⁻ injector, plasma linac, e ⁺ RF linac, BDS.
Surface building	33.26	1,267	1,944	2,830	CLIC	Used for drive-beam linac
Cut-and-cover tunnel	9.86	2,035	2,712	3,597	CLIC	Used for drive-beam linac and combiner rings

Cost element (per volume)	Cost/volume (kILCU/m ³)	Volume (m ³)			Ref.	Comment
		250 GeV	380 GeV	550 GeV		
Tunnel (boring machine)	0.573	397,190	499,546	621,641	CLIC	Based on outer diameter.
Tunnel widening (excavation)	0.45	148,699	183,328	220,556	FCC	Used in dual BDS widening.
Cut-and-cover tunnel	0.45	44,589	59,423	78,814		Estimate based on tunnel area.

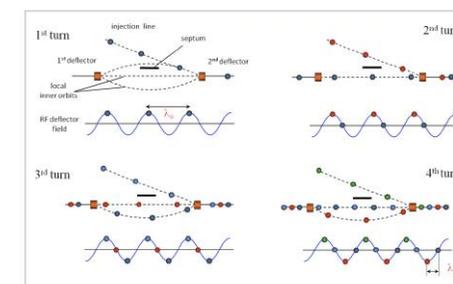
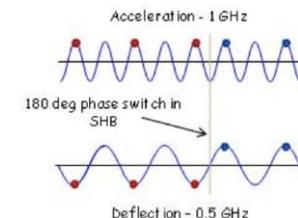
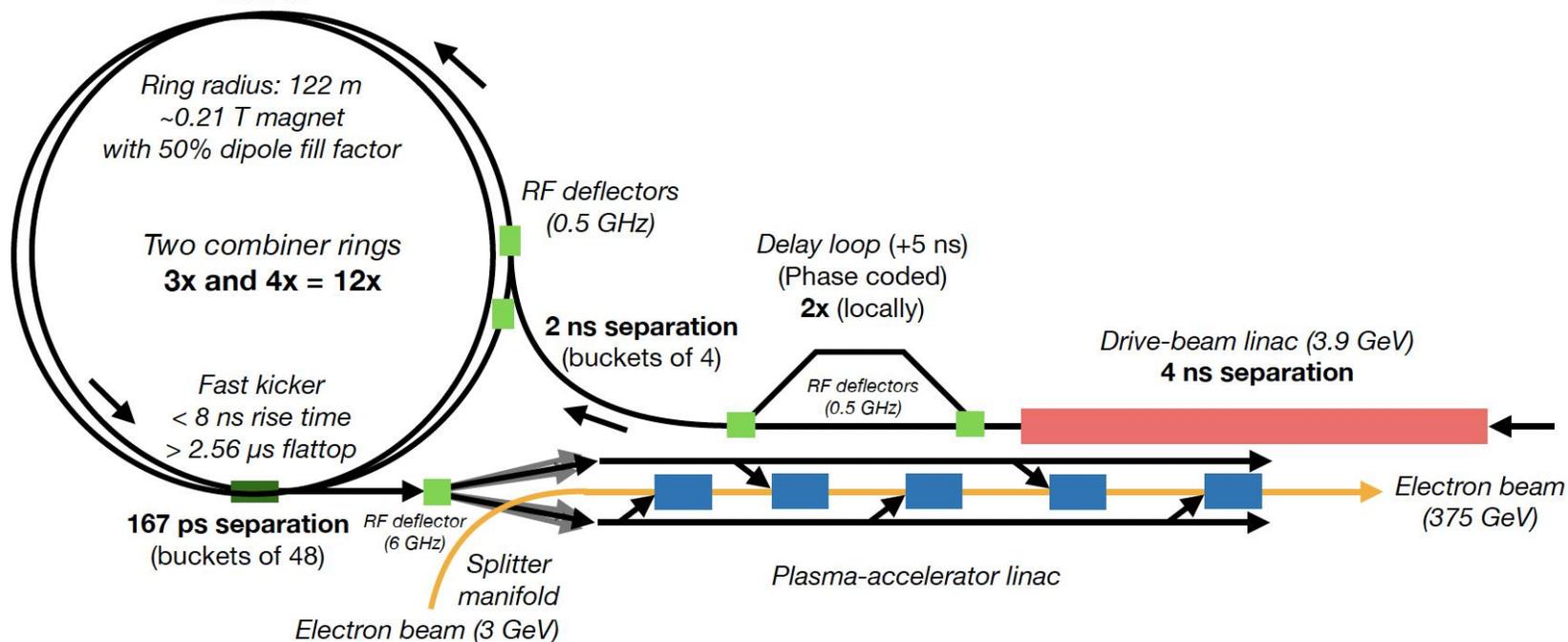
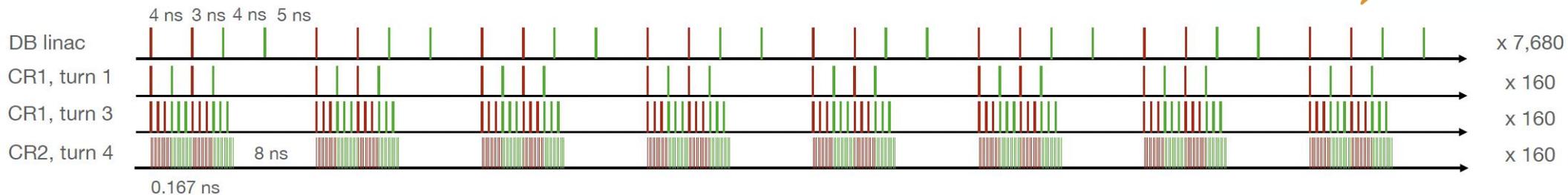
Backup slide — Cost model table (part 2)

Cost element (per power)	Cost/power (MILCU/MW)	Power (MW)			Ref.	Comment
		250 GeV	380 GeV	550 GeV		
Main beam dumps	2.39	12.8	19.5	28.2	ILC	
Driver dumps	2.39	4.8	7.3	10.6		Based on main beam dumps
LN2 re-liquification plant	13.5	2.5	3.9	5.8	C ³	Per power at cryo temp. (↑15% cooling eff. at 77 K)
Klystron (S-band)	0.009	20,787	31,173	44,775	C ³	Peak power
Modulator (S-band)	0.006	20,787	31,173	44,775	C ³	Peak power
Klystron (L-band)	0.015	8,528	13,137	19,165	CLIC	Peak power
Modulator (L-band)	3.9	42.8	66.0	96.3	CLIC	Average power

Cost element (individual)	Cost (MILCU)	Power (MW)			Ref.	Comment
		250 GeV	380 GeV	550 GeV		
Klystron (S-band, injectors)	0.351	21	21	21	C ³	39 MW peak, 28 kW avg.
Modulator (S-band, injectors)	0.234	21	21	21	C ³	39 MW peak, 28 kW avg.
Klystron (S-band, main linac)	0.603	298	453	656	C ³	67 MW peak, 38 kW avg.
Modulator (S-band, main linac)	0.402	298	453	656	C ³	67 MW peak, 38 kW avg.
Klystron (L-band, driver linac)	0.409	409	630	919	CLIC	21 MW peak, 105 kW avg.
Modulator (L-band, driver linac)	0.313	409	630	919	CLIC	21 MW peak, 105 kW avg.
Waveguides	0.0273	728	1,104	1,596	CLIC	Assumed same for L- & S-band
Low-level RF components	0.0455	728	1,104	1,596	CLIC	Assumed same for L- & S-band
Combiner ring RF kickers	1	6	6	6		Rough estimate (no source).
Polarized positron source	178	1	1	1	ILC	Helical undulator and target. ILC cost minus the RF injector.
Polarized electron source	82	1	1	1	ILC	Photocathode gun. ILC cost minus the RF injector.
Driver source	10	1	1	1		Thermionic gun with relaxed performance. Rough estimate only without source.
Dual IP interaction area	154	1	1	1	CLIC	
Experimental area	20	1	1	1	CLIC	

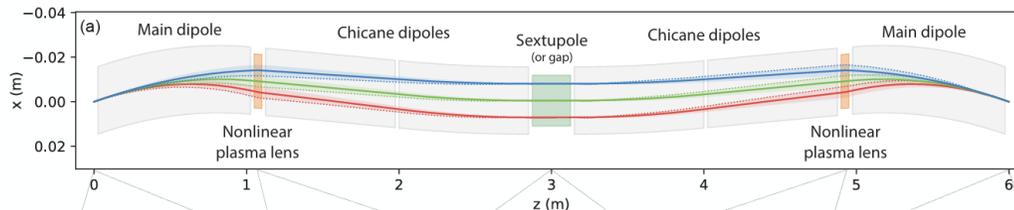
Bunch pattern

Bunch train pattern and combiner rings



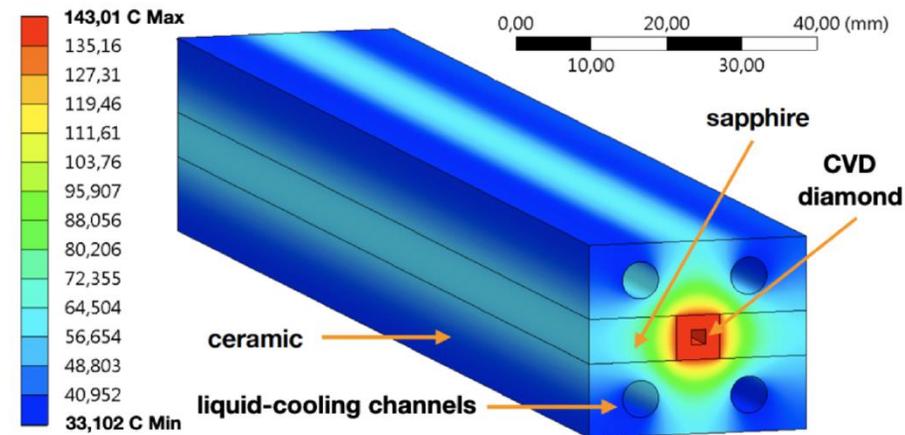
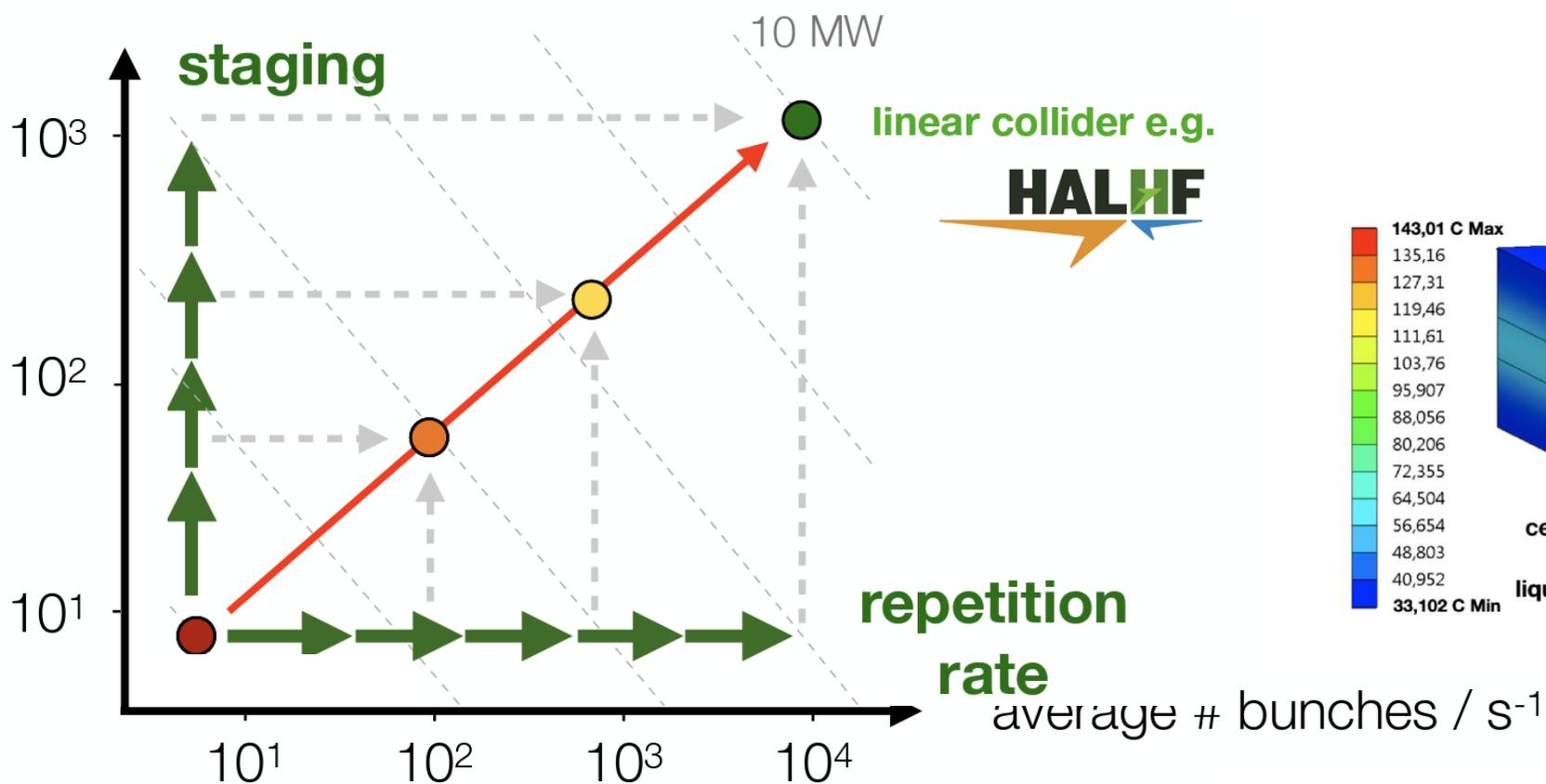
From CLIC CDR (2013)

R&D Topics



Source: Lindstrøm et al. (manuscript in preparation)

E / GeV



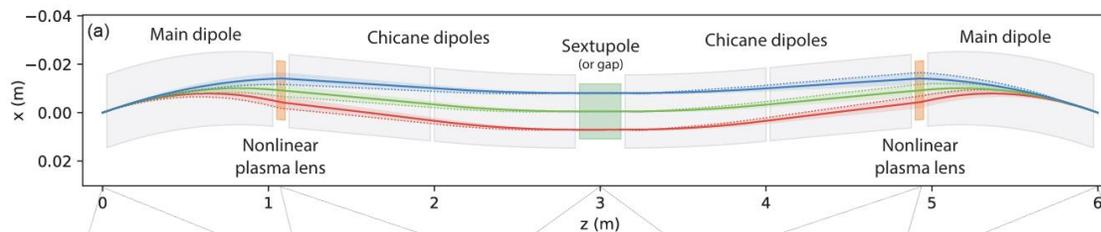
R&D Topics - Staging



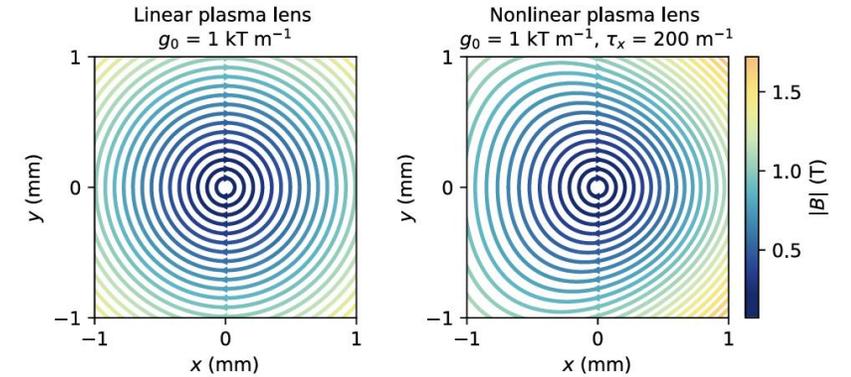
R&D topic – Reaching high energy

Tackling the staging problem with achromatic optics

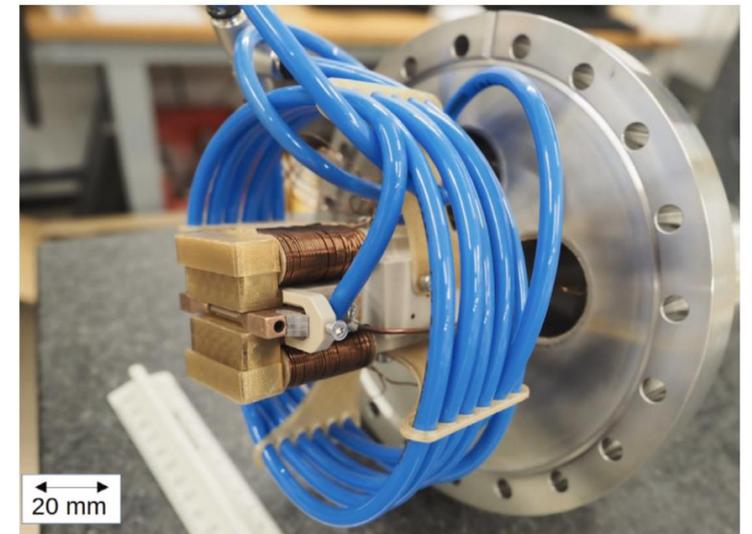
- > The combination of large energy spread and high divergence necessitates achromatic optics.
- > New achromatic solution proposed, based on local chromaticity correction (*with **nonlinear plasma lenses***) in a chicane
- > These optics and plasma lenses are being developed as part of the SPARTA project



Source: Lindstrøm et al. (manuscript in preparation)



Source: Lindstrøm et al. (manuscript in preparation)



SPARTA nonlinear plasma lens (Uni. Oslo).
Source: Drobnik et al. NIM A 1072, 170223 (2025)

R. Tomas et al., Smallest vertical beam sizes achieved in high energy accelerators.
<https://arxiv.org/pdf/2506.12361>

Challenges:

Emittances: Factor 10-100

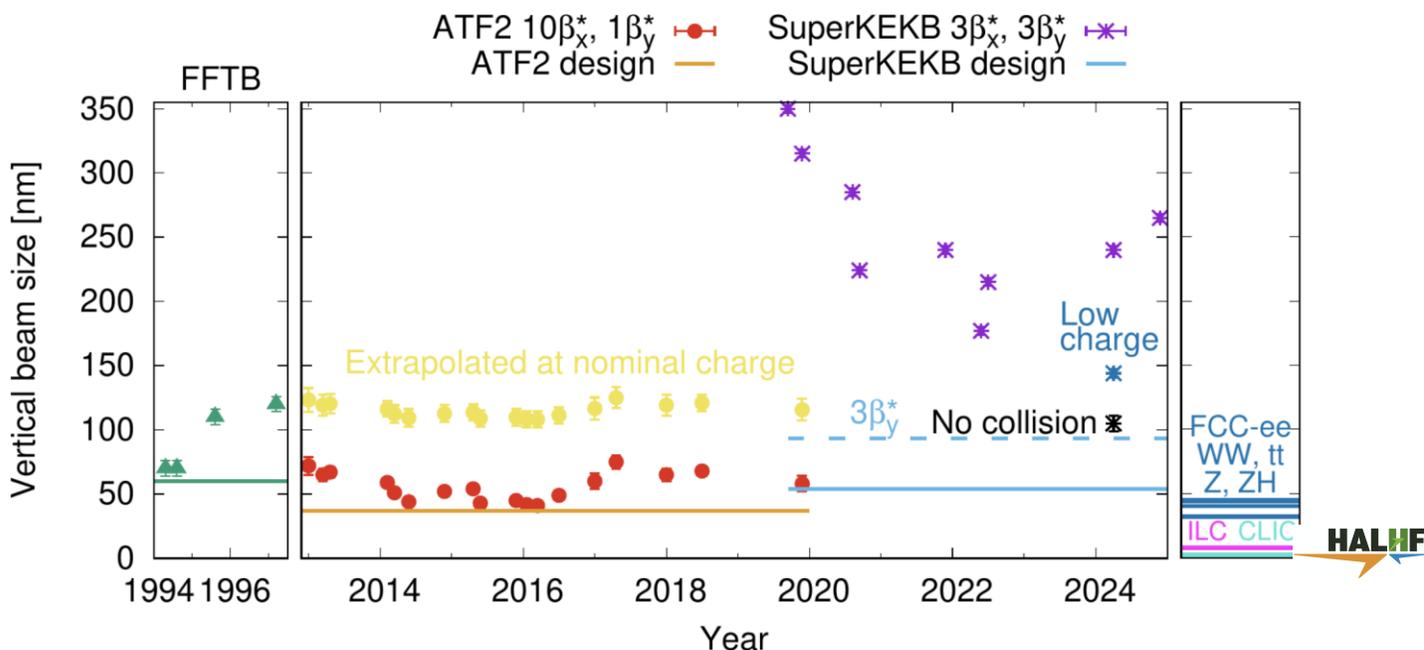
larger than in previous designs;

β_x : Factor 2-4 smaller

=> Longer than current design

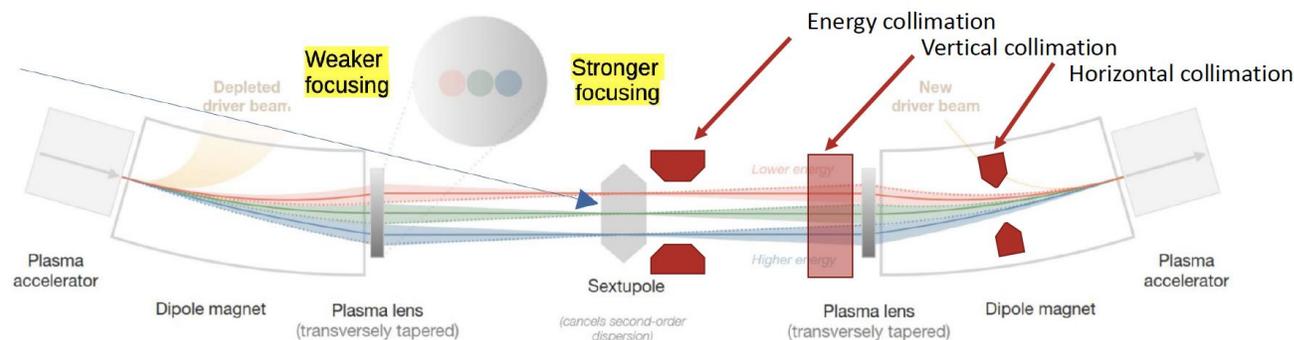
beyond 250 GeV

See R. Thomas talk
@ LCWS25



HALHF Workshop 2024, A. Serji

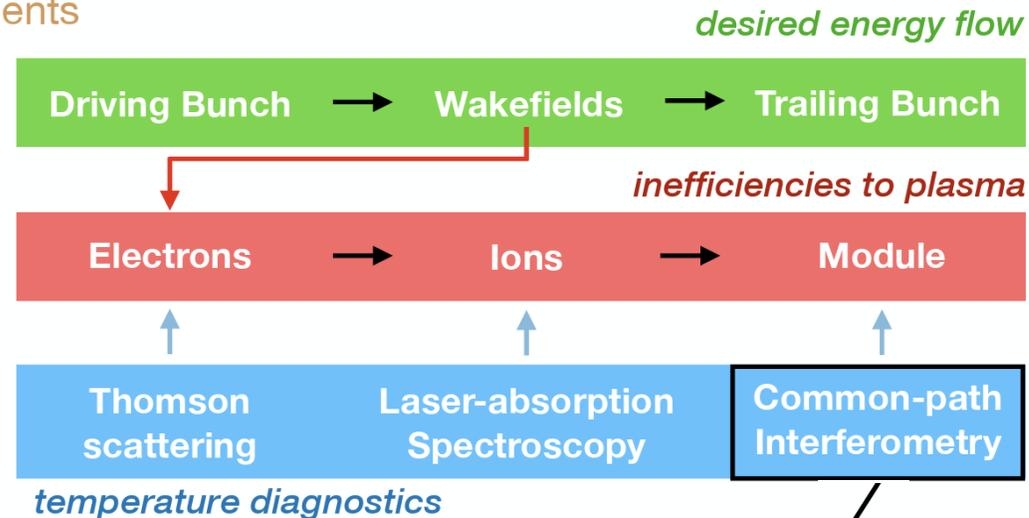
Distributed collimation in plasma sections – for HALHF design



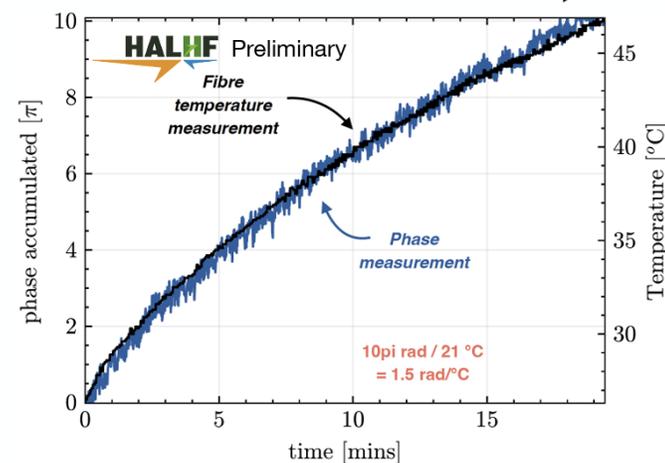
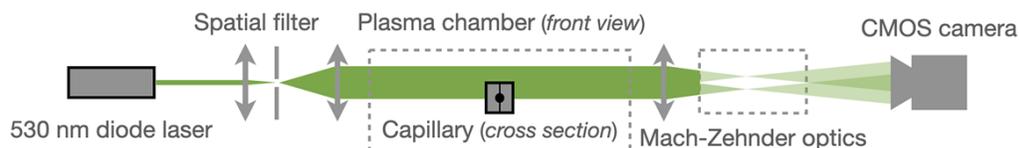
R&D Topics - Plasma Cell

Novel diagnostic package for direct temperature measurements

- > **Need (direct) temperature diagnostics** of all inefficient energy-transport channels
- > **All-optical diagnostics** for non-invasive implementation at different plasma facilities
- > Diagnostic package being developed and benchmarked in a dedicated Oxford laboratory



- > Temperature evolution of a discharge capillary by tracking the temperature-dependent phase shift from heating/expanding sapphire plates



Selected Updates

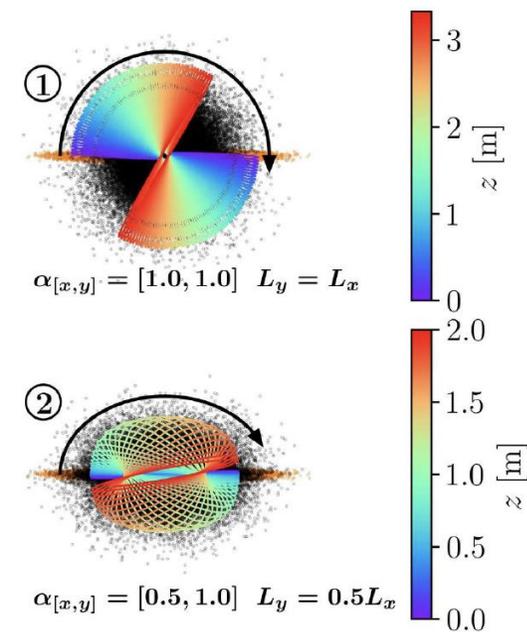
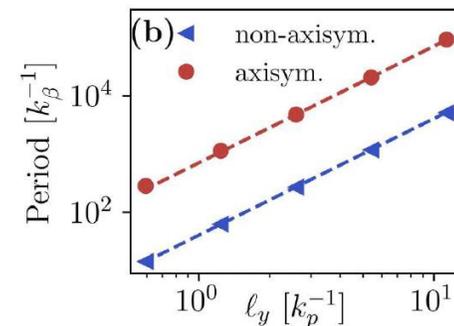
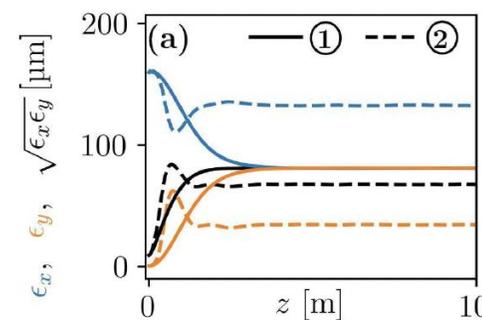
- PWFA arm:

- 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



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**

Timeline (approximate / aggressive / aspirational)				
0–5 years	5–10 years	10–15 years	15–20 years	20+ years
<p>Pre-CDR & CDR (HALHF)</p> <p>Simulation study to determine self-consistent parameters (demonstration goals)</p> <p>First proof-of-principle experimentation</p>	<p>Demonstration of: Scalable staging, driver distribution, stabilisation (active and passive)</p>	<p>Multistage tech demonstrator Strong-field QED experiment (25–100 GeV e⁻)</p>		<div style="border: 1px solid black; padding: 5px;"> <p> Feasibility study</p> <p> R&D (exp. & theory)</p> <p> HEP facility (earliest start of construction)</p> </div>
	<p>Demonstration of: Preserved beam quality, high rep. rate, plasma temporal uniformity & cell cooling</p>	<p>Avg. power tech demonstrator X-ray FEL (20 GeV e⁻)</p>		

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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)	Multistage tech demonstrator Strong-field QED experiment (25–100 GeV e ⁻)	(Facility upgrade) (Facility upgrade)	
	Demonstration of: Preserved beam quality, high rep. rate, plasma temporal uniformity & cell cooling	Avg. power tech demonstrator X-ray FEL (20 GeV e ⁻)		
	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.)		

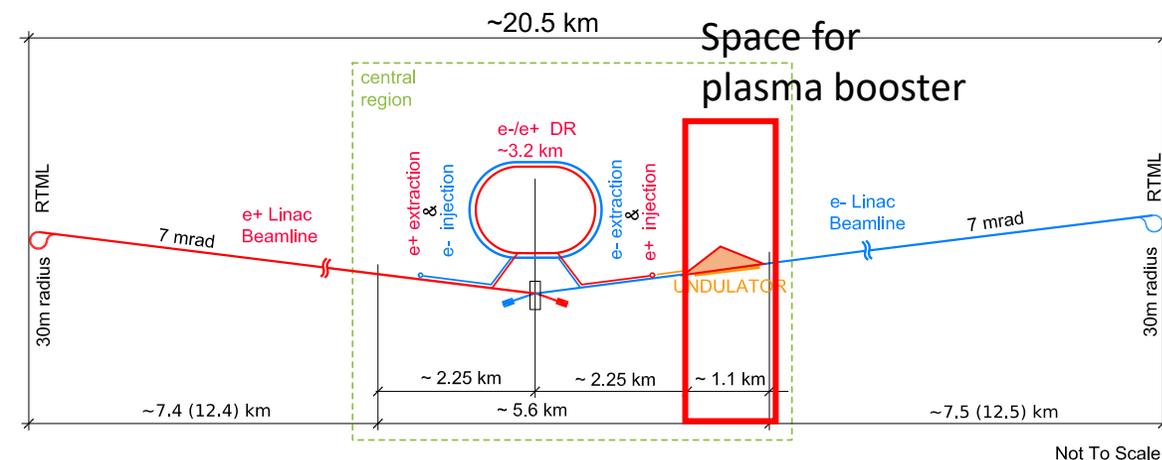
Path to construction

- > 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**
- > Long term (15–20 yrs): Delivery of HALHF — **intense R&D required**
- > Upgrades (20+ yrs): Upgrade path for HALHF (many options available)

Timeline (approximate / aggressive / aspirational)				
0–5 years	5–10 years	10–15 years	15–20 years	20+ years
<p>Pre-CDR & CDR (HALHF)</p> <p>Simulation study to determine self-consistent parameters (demonstration goals)</p> <p>First proof-of-principle experimentation</p>	<p>Demonstration of:</p> <p>Scalable staging, driver distribution, stabilisation (active and passive)</p>	<p>Multistage tech demonstrator</p> <p>Strong-field QED experiment (25–100 GeV e⁻)</p>	<p>(Facility upgrade)</p> <p>(Facility upgrade)</p>	<div style="border: 1px solid black; padding: 5px;"> <p> Feasibility study</p> <p> R&D (exp. & theory)</p> <p> HEP facility (earliest start of construction)</p> </div>
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	<p>R&D into conventional-accelerator & particle-physics concepts</p> <p>Demonstration of:</p> <p>High wall-plug efficiency (e⁻ drivers) & spin polarisation</p>	<p>Higgs factory (HALHF)</p> <p>Asymmetric, plasma–RF hybrid collider (250–380 GeV c.o.m.)</p>	<p>(Facility upgrade)</p>	
	<p>Demonstration of:</p> <p>Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser drivers), ultra-low emittances, energy recovery schemes, compact beam-delivery systems</p>	<p>Multi-TeV e⁺–e⁻/γ–γ collider</p> <p>Symmetric, all-plasma-based collider (> 2 TeV c.o.m.)</p>		

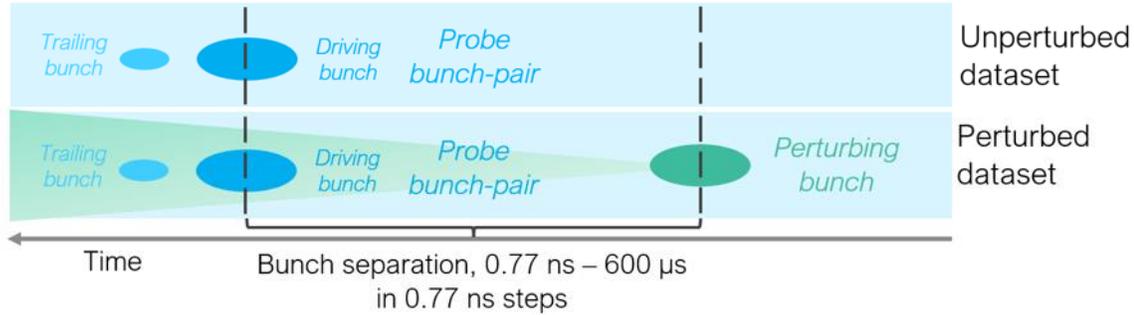
Upgrade Existing LC

- Technology being developed for HALHF could also enhance a “conventional” LC design – part of “LCVision”:
- Assume: ILC has been built, -> 2x125GeV linacs available
- Goal: upgrade electron arm to 500GeV with plasma
-> 125x500GeV -> 500GeV COM; $\gamma \sim 1.2$
-> upgrade a Higgs factory to a tth / Zhh factory
- Use electron linac for drive and witness beam:
run a lower gradient but higher current, upgrade RF on electron arm
- Use space for undulator source between electron ML and BDS to install plasma booster
- Feed boosted electrons into existing BDS (laid out for 500GeV)

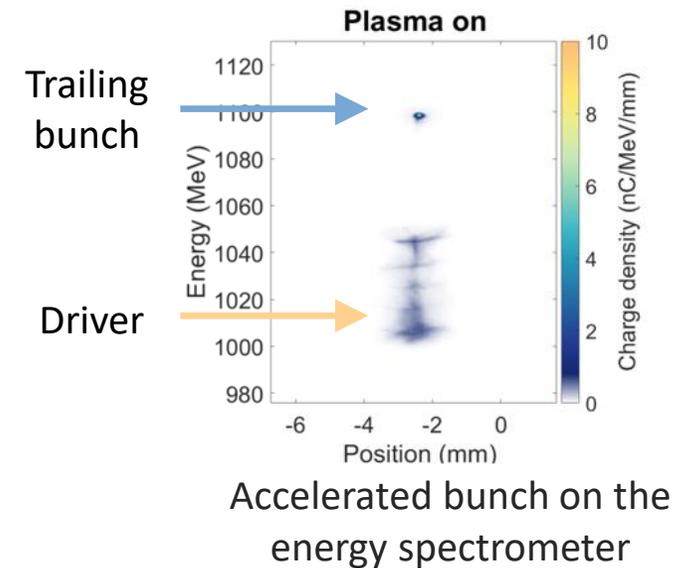
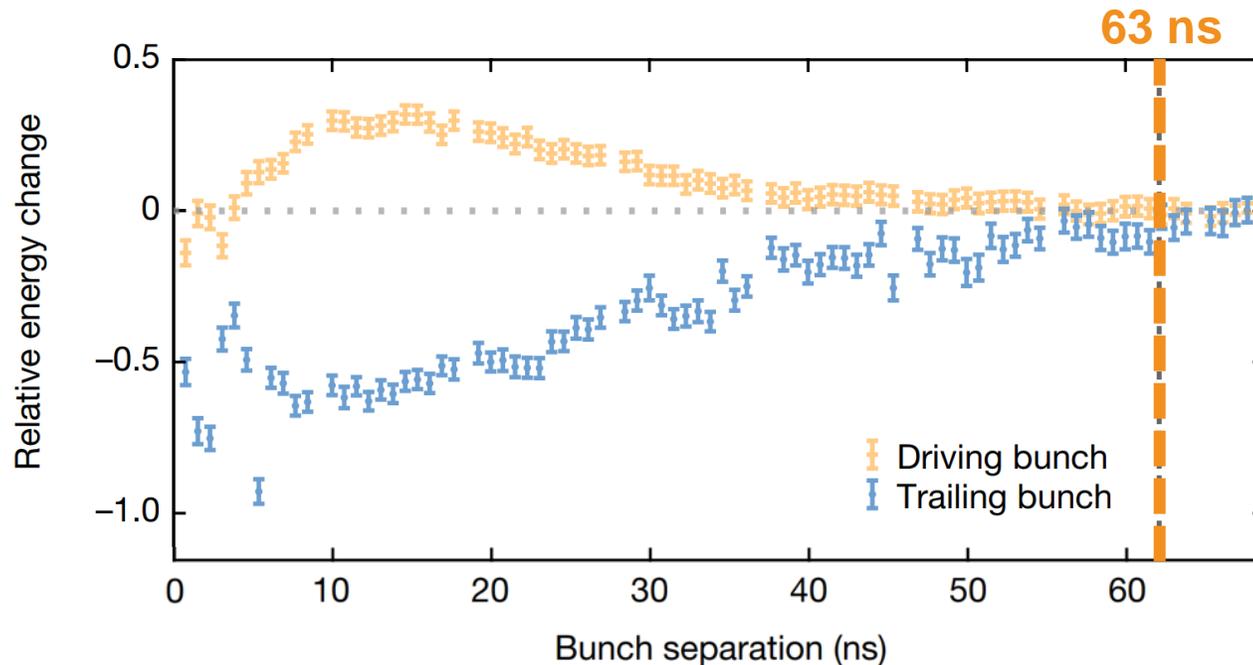


(B. List)

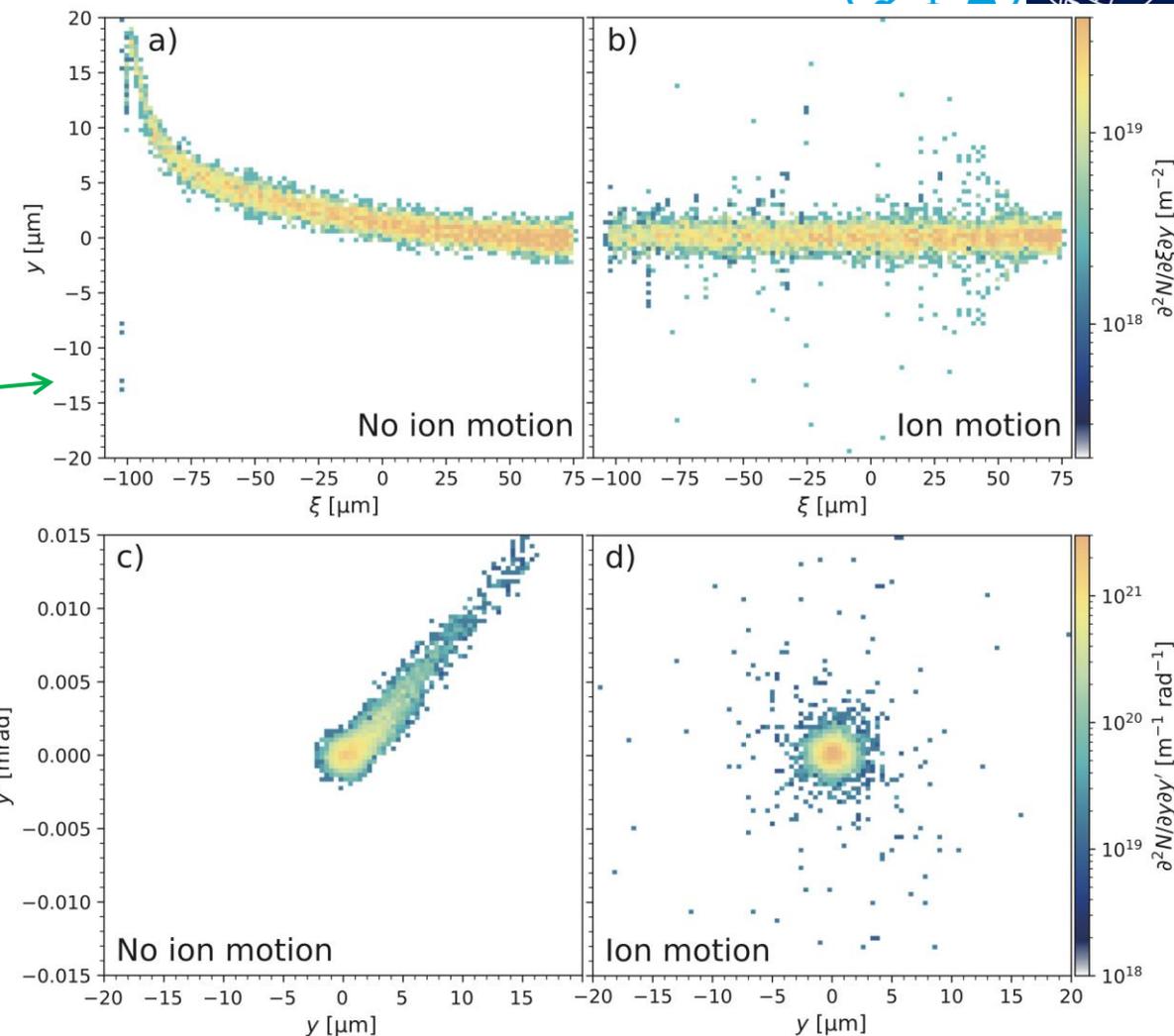
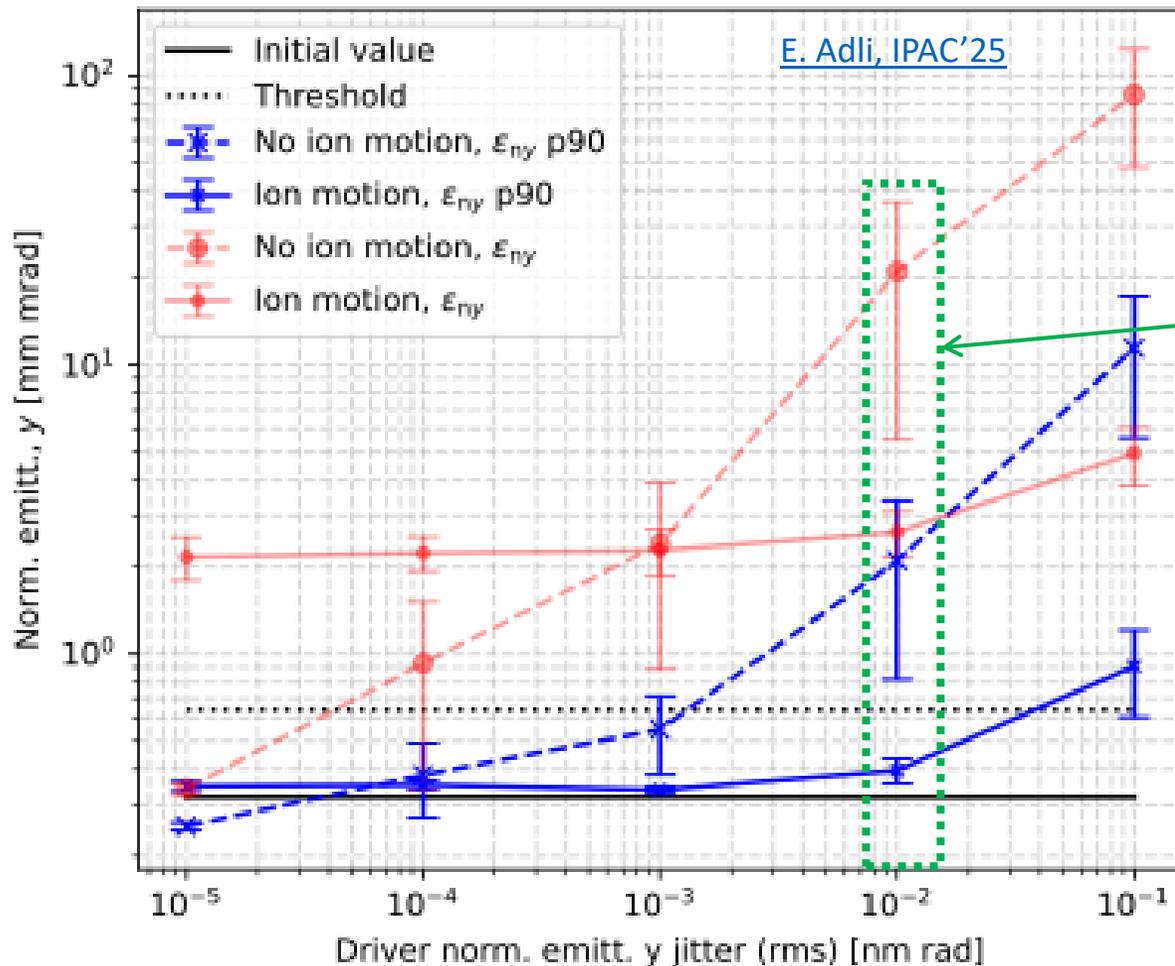
Rate limits in Plasma



Demonstrates >10 MHz repetition
Rate in Ar – lighter gases faster.



At the end of the HALHF linac:

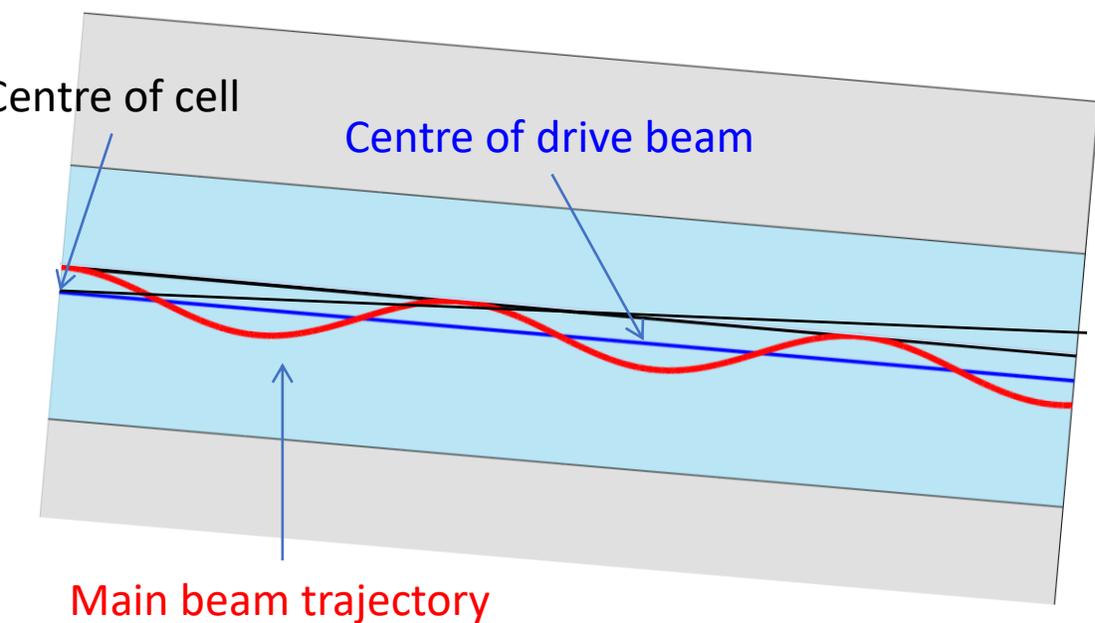


Preliminary results for HALHF (simplified interstage, driver guiding assumed): With no ion motion, the BBU is large. With ion motion, the BBU is efficiently mitigated up **10^{-2} nm rad drive-beam jitter-emittance** – “state of the art” FLASH@DESY - **position jitter of ~ 30 nm**. A halo of large amplitude particles has formed, driving up the rms emittance, while the 90-percentile emittance is better preserved. B. Foster, HK, 01/26

Importance of driver guiding

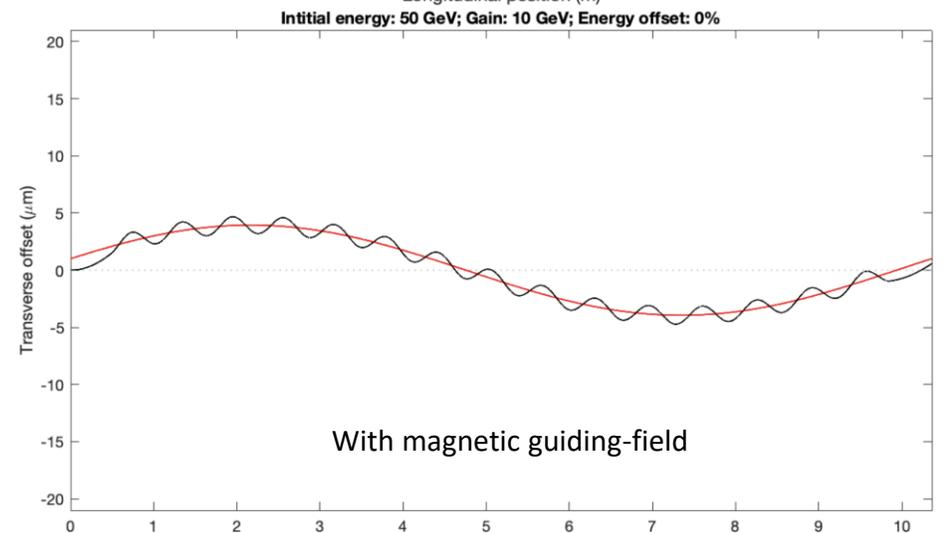
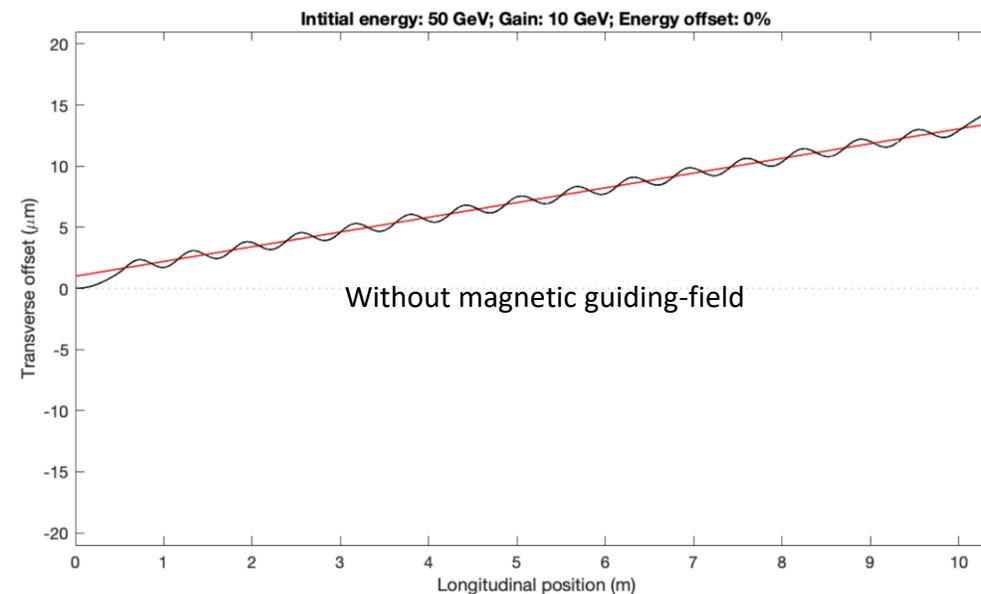
Mitigation: guiding driver with an external magnetic field, here simulated in HiPACE++ (radially focusing field).

Driver injection angle:
may lead to large main beam offset

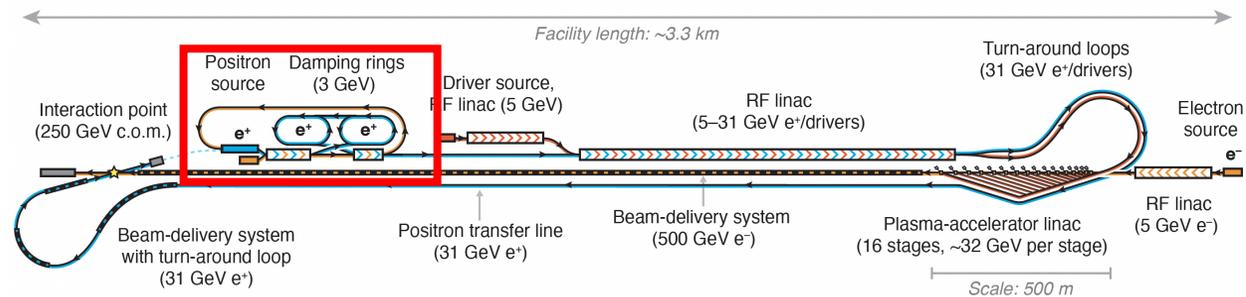


Driver guiding has been assumed in the following ABEL simulations

B. Foster, HK, 01/26

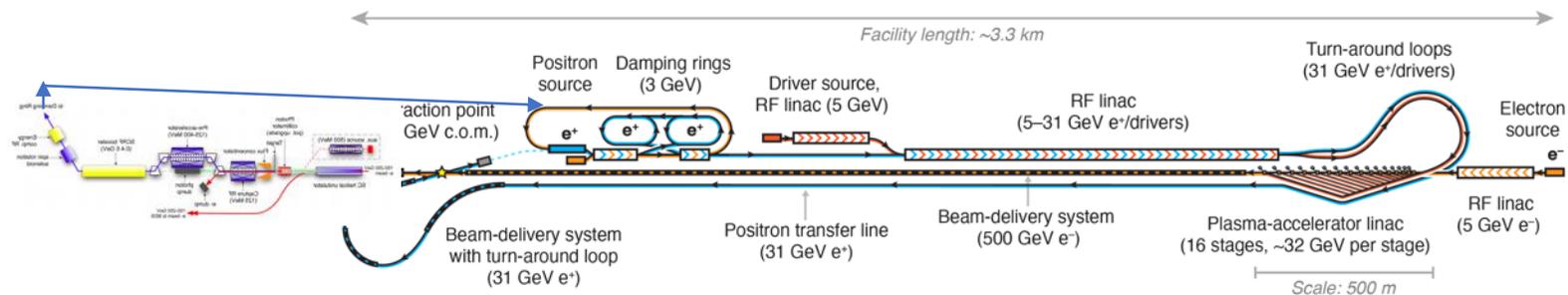


Positron Source



- “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 ($4 \cdot 10^{10} e^+$)).
- May be possible to use spent e^+ bunch after collision rather than dedicated e^- bunch, with cost savings.

Polarized e^+



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

