Applications of Plasma-Wakefield Accelerators to Particle Colliders

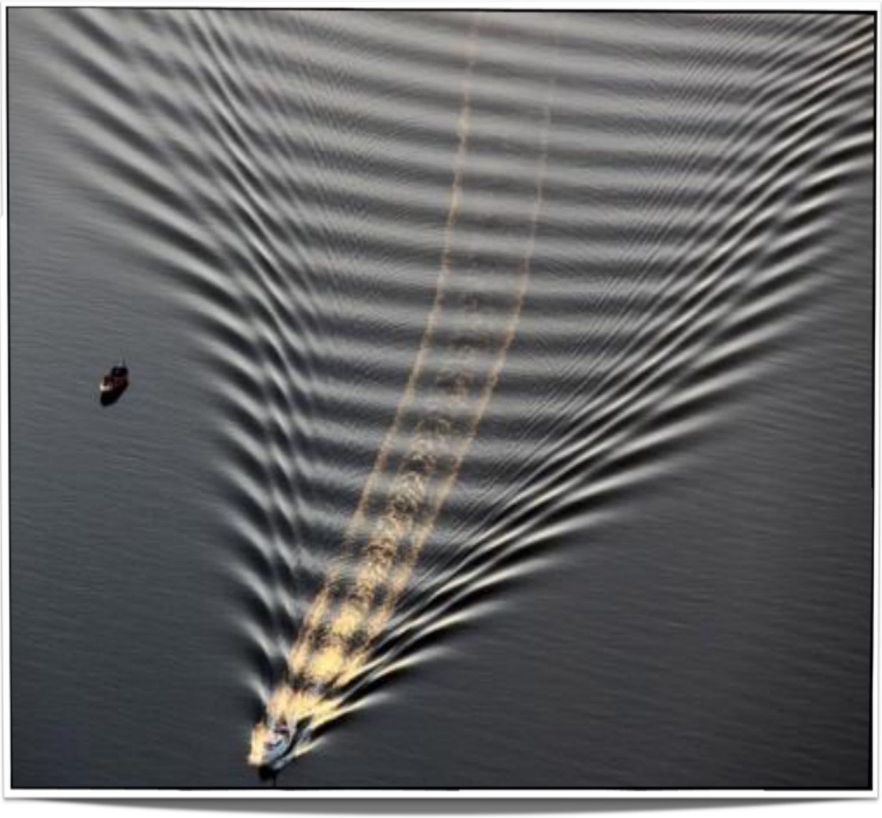
Brian Foster (Oxford)

Humboldt Kolleg
Kitzbühel
June 29th 2022

Outline

- **Introduction to Plasma Acceleration**
- **Applications to Colliders**
  - Injectors
  - Booster/afterburner
  - Stand-alone colliders
- **Summary**

Plasma Wave Acceleration

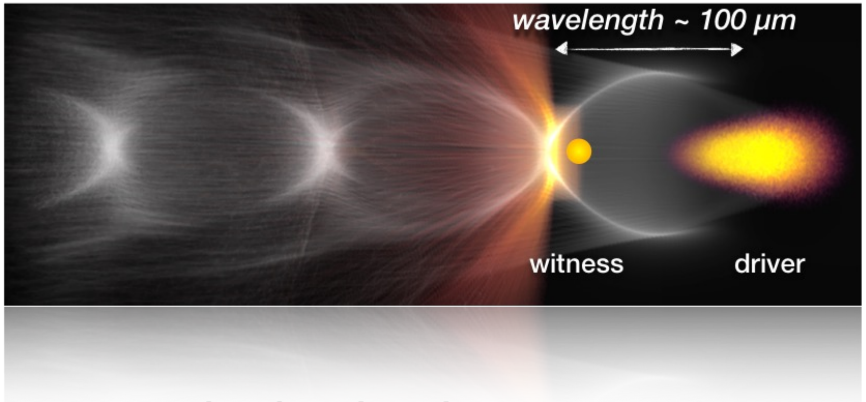


Wake Excitation

Particle Acceleration

Plasma Wave Acceleration

Charge density wave in a plasma

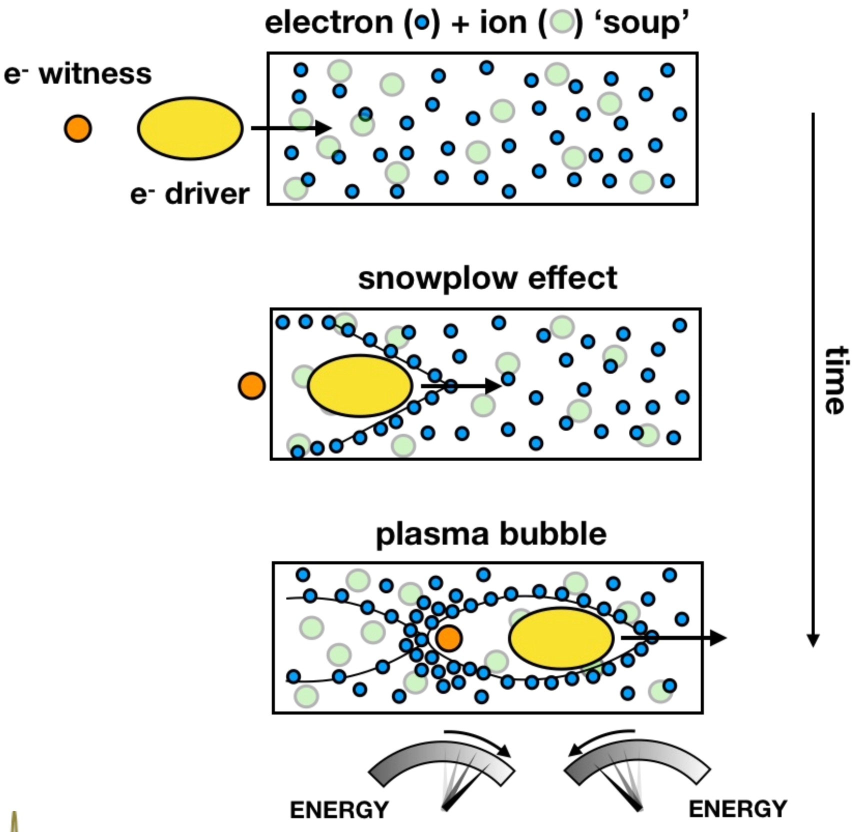


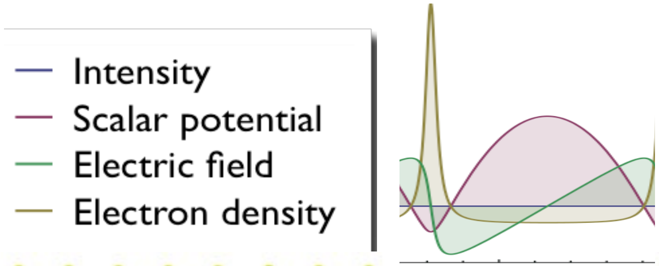
Femtosecond pulse duration

Intrinsically short due to short plasma wavelength

GV/m acceleration gradients

No surface quality limitations → $\mathbf{E_z}$ **in GV/m range**





Collider Applications

- ~40th anniversary of 1st workshop on PWFA for pp – 3 years after Tajima and Dawson. There has been no user-orientated pp application in the interim.
- Applications in colliders governed by ability to produce required luminosity:
- Event rate = $\sigma \mathcal{L}$;
- $\mathcal{L} = N_1 N_2 f n_b / (4\pi\sigma_x\sigma_y)$
- $\mathcal{L} \propto \eta P_{wall}/\sigma_x\sigma_y$
- Point-like cross section goes like $1/E^2_{CM}$ – so to get the same number of events, $\mathcal{L}$ must increase like s.
- In the end, getting power into beams is the show-stopper – but lots of other potential ones on the way.
- Some warning remarks:

○ L/PWFA can show wonderful results – generally as one-offs, on a good day, when all the stars align. For a user machine like a collider – the stars must align 24/7.

○ Reproducibility, reliability are key.

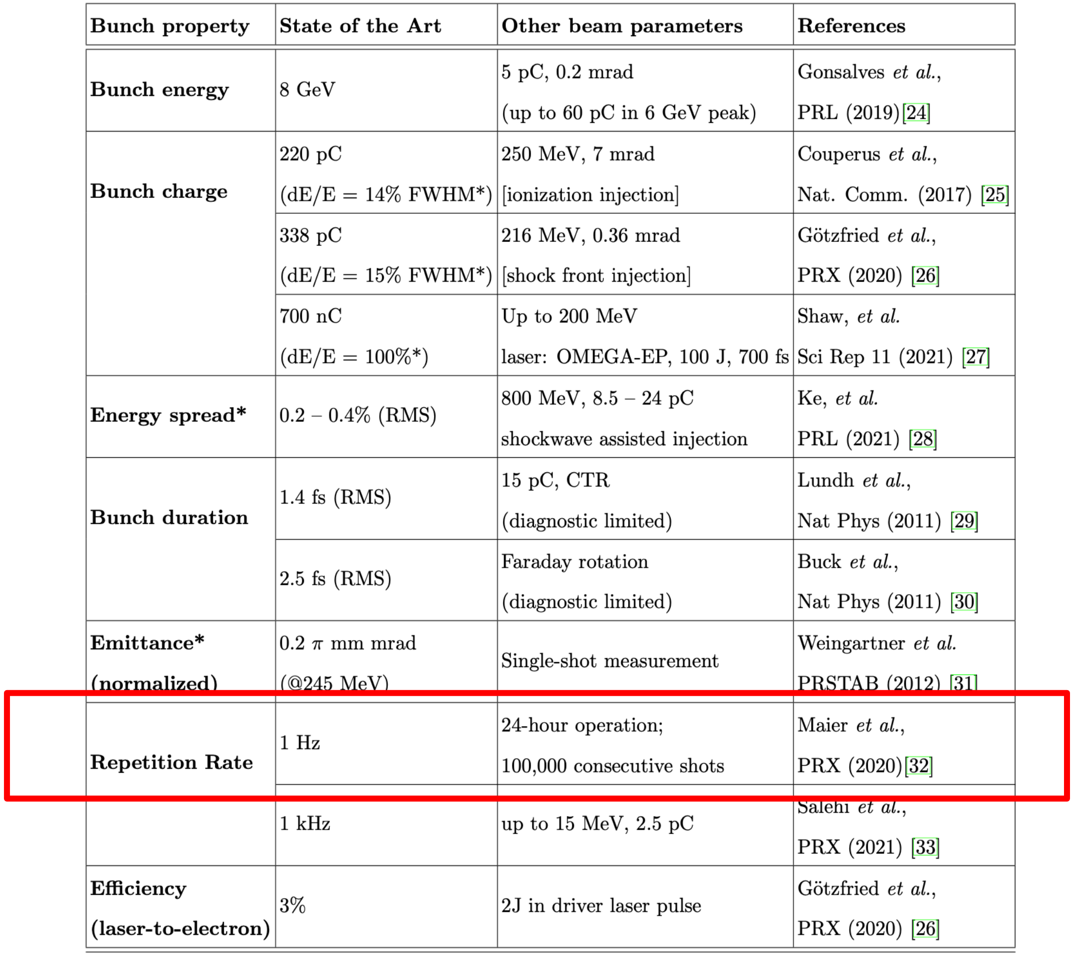
○ Positrons! Beam Delivery System (BDS)! (see Adli, JINST 17 (2022) 05, T05006)

○ I concentrate on L/PWFA.

Injectors

- An obvious use of L/PWFA – intrinsically tiny "feature-size" promises intrinsically excellent 6D emittance – low energy, no staging required. But archetypically the area where reliability crucial. Some applications need low rep. rate.
- What is state of art?

Plasma-Based Particle Sources, Fuchs et al., Snowmass2021, arXiv:2203.08379

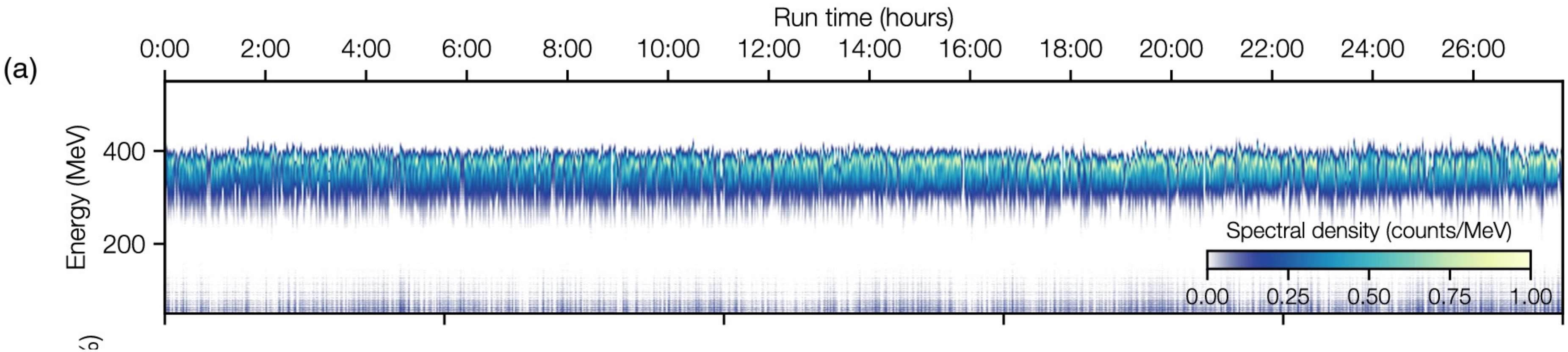


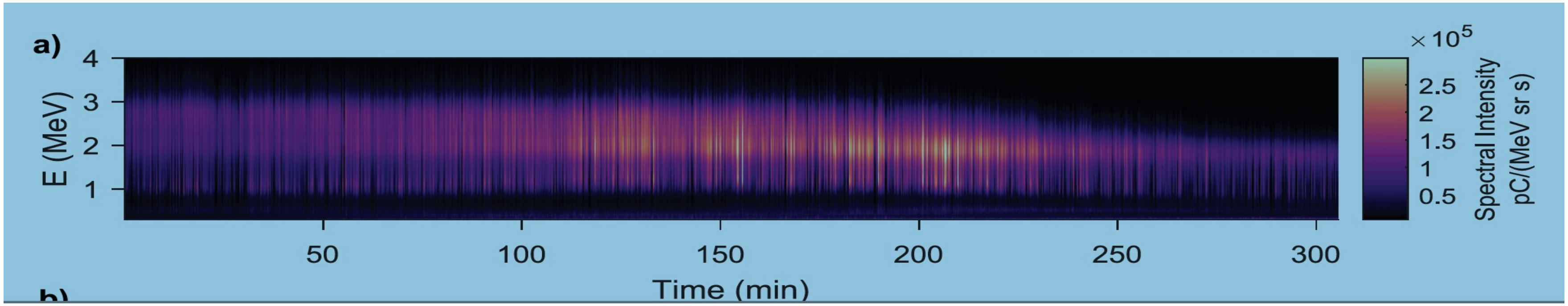
Bunch property	**State of the Art**	**Other beam parameters**	**References**
Bunch energy	8 GeV	5 pC, 0.2 mrad (up to 60 pC in 6 GeV peak)	Gonsalves *et al.*, PRL (2019)[24]
Bunch charge	220 pC (dE/E = 14% FWHM*)	250 MeV, 7 mrad [ionization injection]	Couperus *et al.*, Nat. Comm. (2017) [25]
	338 pC (dE/E = 15% FWHM*)	216 MeV, 0.36 mrad [shock front injection]	Götzfried *et al.*, PRX (2020) [26]
	700 nC (dE/E = 100%*)	Up to 200 MeV laser: OMEGA-EP, 100 J, 700 fs	Shaw, *et al.* Sci Rep 11 (2021) [27]
Energy spread*	0.2 – 0.4% (RMS)	800 MeV, 8.5 – 24 pC shockwave assisted injection	Ke, *et al.* PRL (2021) [28]
Bunch duration	1.4 fs (RMS)	15 pC, CTR (diagnostic limited)	Lundh *et al.*, Nat Phys (2011) [29]
	2.5 fs (RMS)	Faraday rotation (diagnostic limited)	Buck *et al.*, Nat Phys (2011) [30]
Emittance* (normalized)	0.2 π mm mrad (@245 MeV)	Single-shot measurement	Weingartner *et al.* PRSTAB (2012) [31]
Repetition Rate	1 Hz	24-hour operation; 100,000 consecutive shots	Maier *et al.*, PRX (2020)[32]
	1 kHz	up to 15 MeV, 2.5 pC	Salehi *et al.*, PRX (2021) [33]
Efficiency (laser-to-electron)	3%	2J in driver laser pulse	Götzfried *et al.*, PRX (2020) [26]

TABLE I. **Overview of the state-of-the art LWFA electron beam parameters.**

Injectors

- Perhaps most obvious use of L/PWFA – intrinsically tiny “feature-size” promises intrinsically excellent 6D emittance – low energy, no staging required. But archetypically the area where reliability crucial.
- What is state of art?

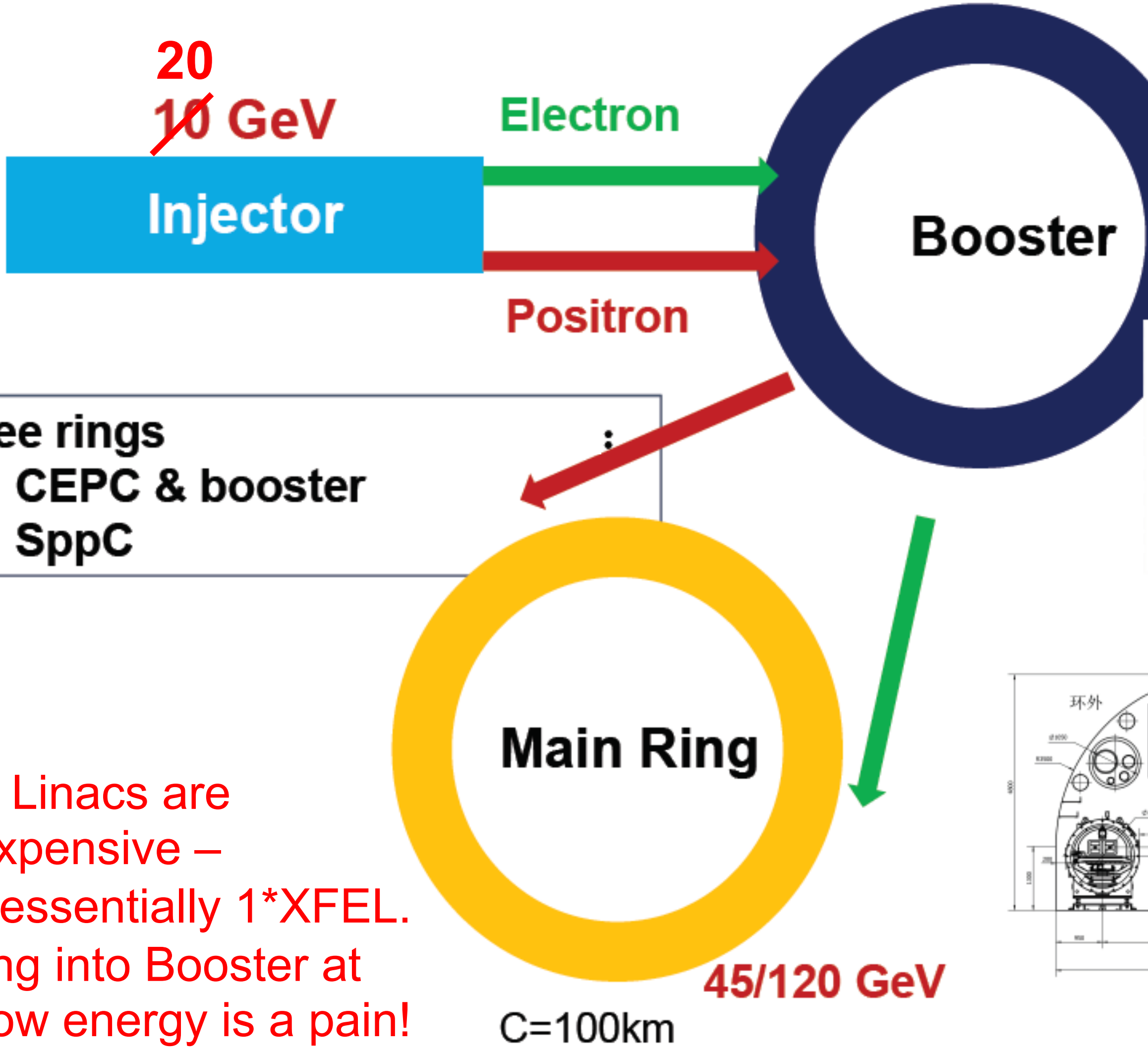




L. Rovige et al., Phys. Plasmas 28, 033105 (2021)

Injectors - CEPC

CEPC Accelerator CDR Status and Perspectives towards TDR
Jie Gao (Institute of High Energy Physics, Chinese Academy of Sciences)



20
~~10~~ GeV

Electron

Injector

Booster

Positron

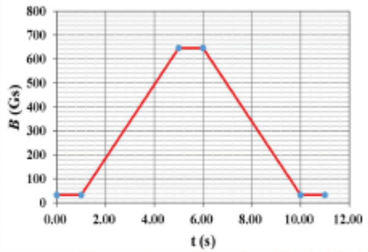
Energy Ramp
10 ->45/120GeV

Three rings :
- **CEPC & booster**
- **SppC**

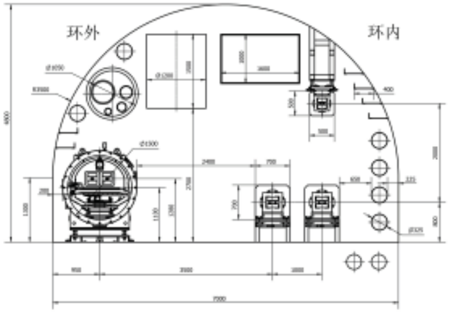
Main Ring

45/120 GeV

C=100km



Booster Cycle (0.1 Hz)

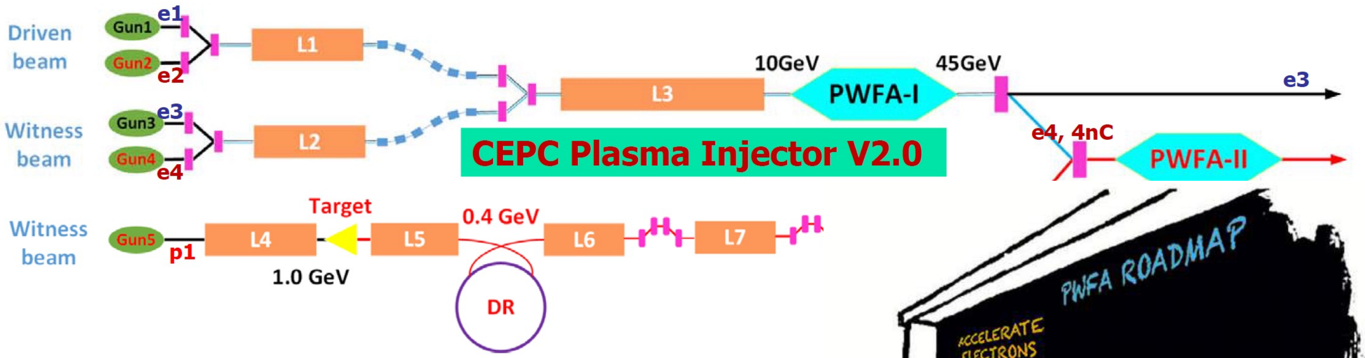


BUT – Linacs are
very expensive –
this is essentially 1*XFEL.
Injecting into Booster at
such low energy is a pain!

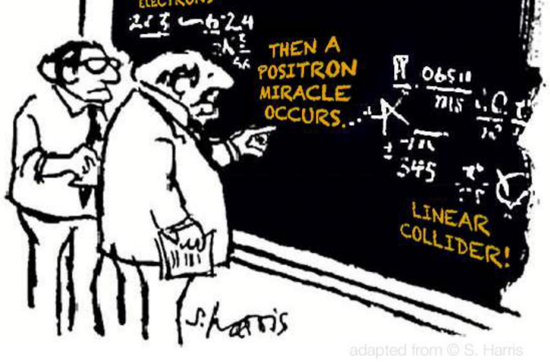
CEPC PWFA Linac

Booster Requirement	
Energy (GeV)	45.5 (0.2%)
Bunch Charge (nC)	0.78
Bunch length(um)	<3000
Energy Spread(%)	0.2
ε_N(μm·rad)	<800
Bunch Size(um)	<2000

- Electron Acceleration → HTR
- Positron Acceleration → Stable mode
- Conventional Accelerator optimization
- Beam manipulations



- Uniquely useful for green-field site – FCCee? No.
- But e^+? Linear wakes can symmetrise e^+/e^- but only with low efficiency, high emittance, low gradient. Non-linear?

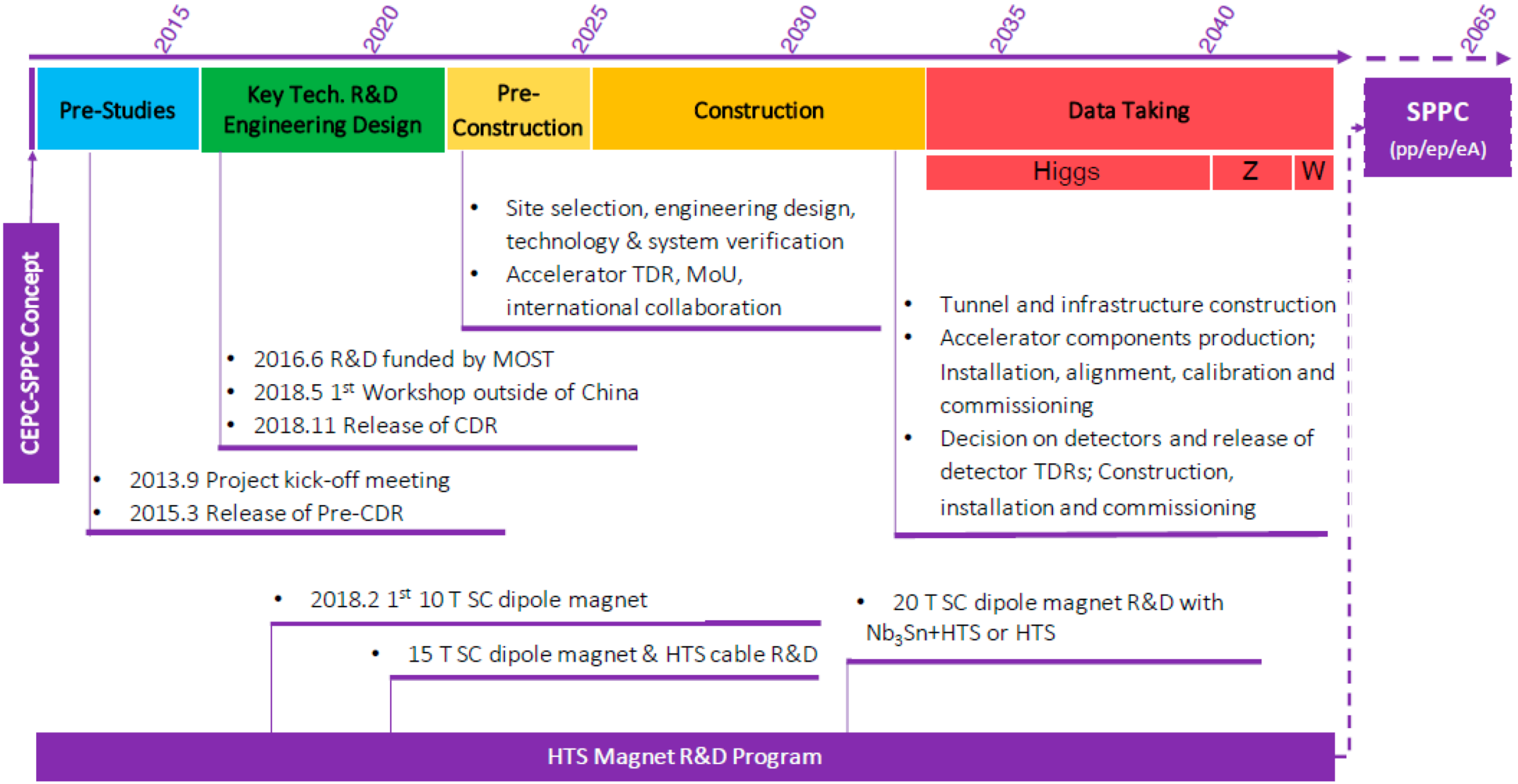


adapted from © S. Harris

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

CEPC Timeline

CEPC Project Timeline



- 2013.9 Project kick-off meeting
- 2015.3 Release of Pre-CDR

- 2016.6 R&D funded by MOST
- 2018.5 1st Workshop outside of China
- 2018.11 Release of CDR

- Site selection, engineering design, technology & system verification
- Accelerator TDR, MoU, international collaboration

- Tunnel and infrastructure construction
- Accelerator components production; Installation, alignment, calibration and commissioning
- Decision on detectors and release of detector TDRs; Construction, installation and commissioning

- 2018.2 1st 10 T SC dipole magnet
- 15 T SC dipole magnet & HTS cable R&D
- 20 T SC dipole magnet R&D with Nb_3Sn+HTS or HTS

Outline

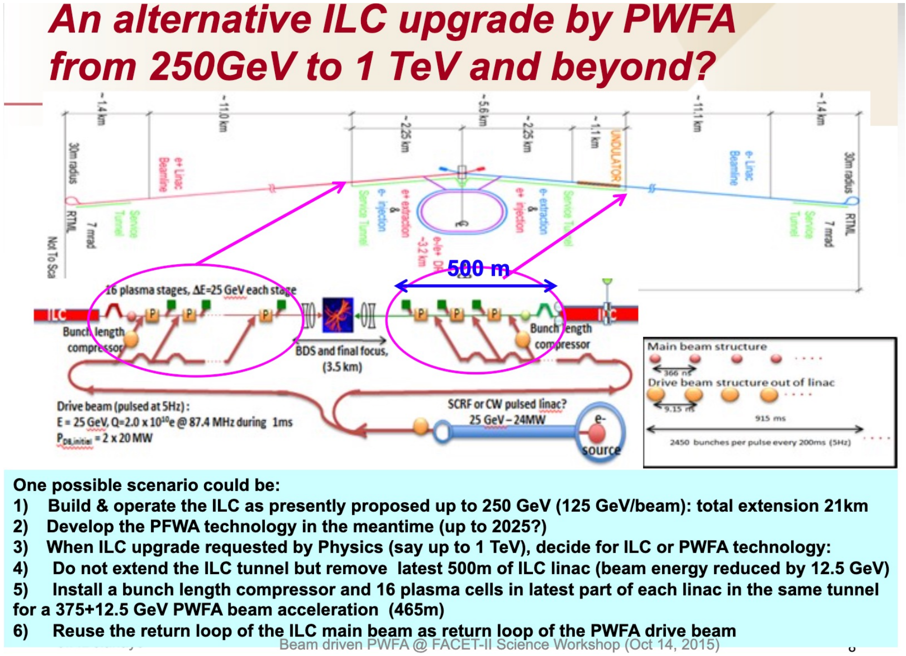
- **Introduction to Plasma Acceleration**

- **Applications to Colliders**
  - Injectors
  - Booster/afterburner
  - Stand-alone colliders

- **Summary**

Booster/Afterburner

- Need to match beam delivered to L/PWFA to give optimum results. Because it sits inside conventional accelerator, many problems such as staging amenable to conventional solutions – easier? Collider more difficult than boosting XFEL because staging, positrons required in addition to rep. rate.
- Again, reliability/reproducibility at a premium.
- E.g. add plasma stages to boost ILC from Higgs Factory to 500 GeV/1 TeV



An alternative ILC upgrade by PWFA from 250GeV to 1 TeV and beyond?

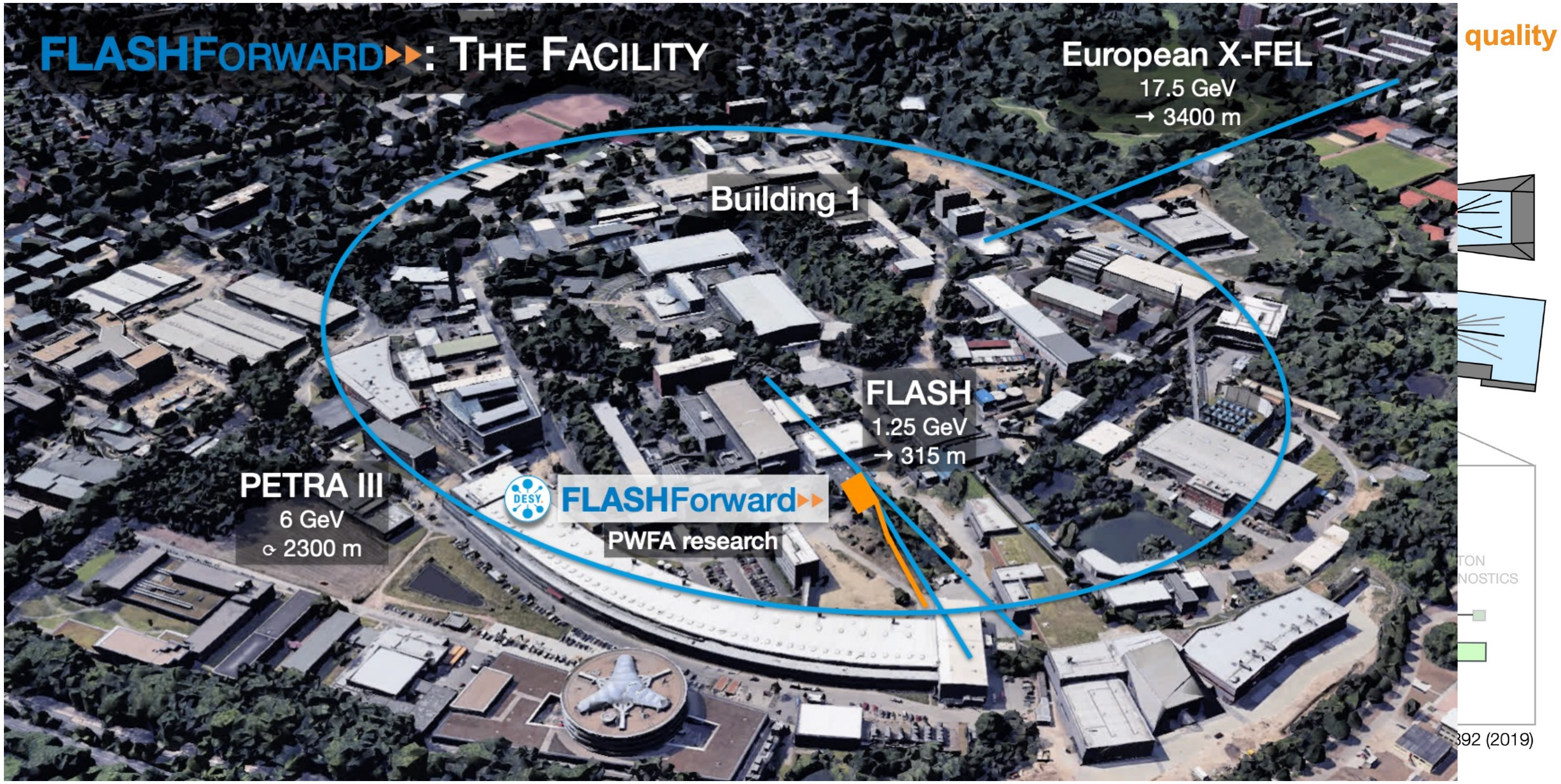
One possible scenario could be:

1) **Build & operate the ILC as presently proposed up to 250 GeV (125 GeV/beam): total extension 21km**
2) **Develop the PFWA technology in the meantime (up to 2025?)**
3) **When ILC upgrade requested by Physics (say up to 1 TeV), decide for ILC or PWFA technology:**
4) **Do not extend the ILC tunnel but remove latest 500m of ILC linac (beam energy reduced by 12.5 GeV)**
5) **Install a bunch length compressor and 16 plasma cells in latest part of each linac in the same tunnel for a 375+12.5 GeV PWFA beam acceleration (465m)**
6) **Reuse the return loop of the ILC main beam as return loop of the PWFA drive beam**

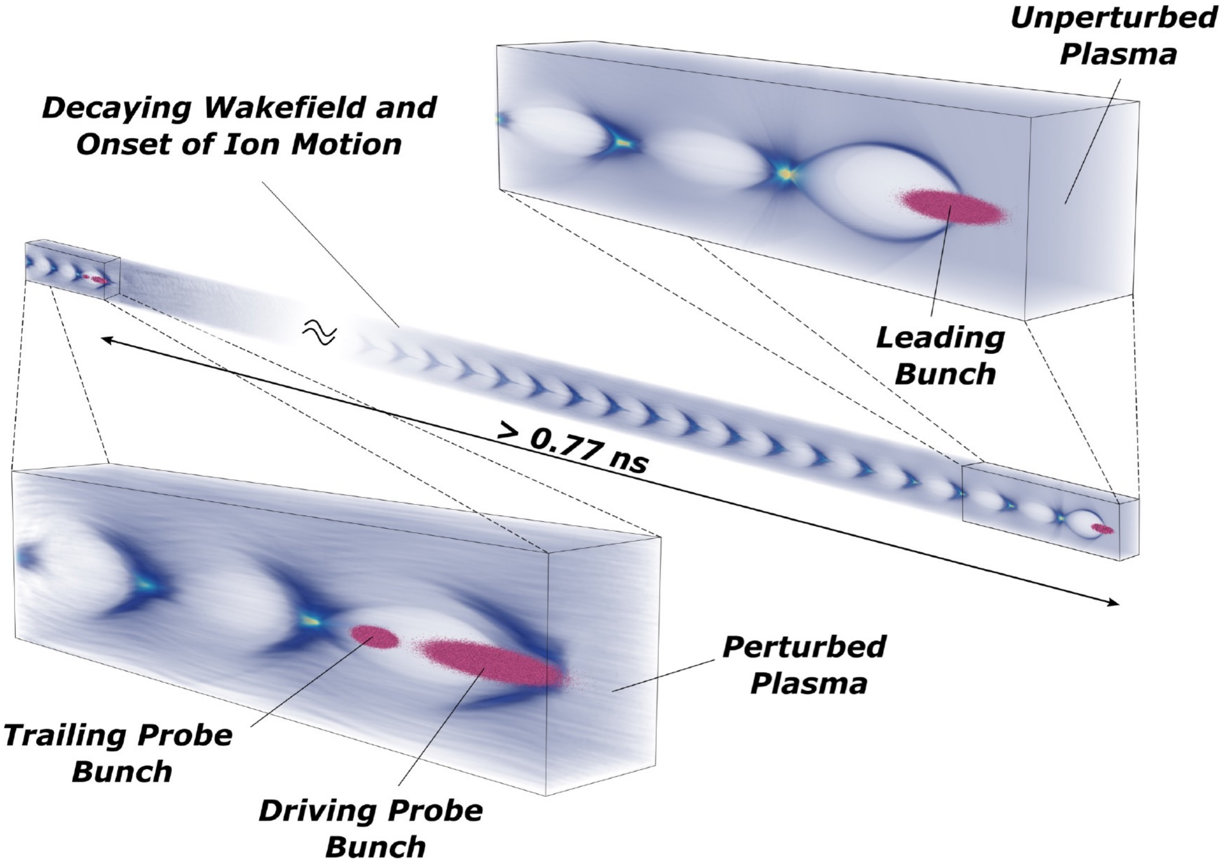
Beam driven PWFA @ FACET-II Science Workshop (Oct 14, 2015)

Basic L/PWFA limits - Rates

- Need to understand how plasma reacts to beam structure of “conventional” accelerators – what are the limits and are they compatible with afterburner requirements?
- FLASHForward results on maximum repetition rate from basic plasma relaxation.



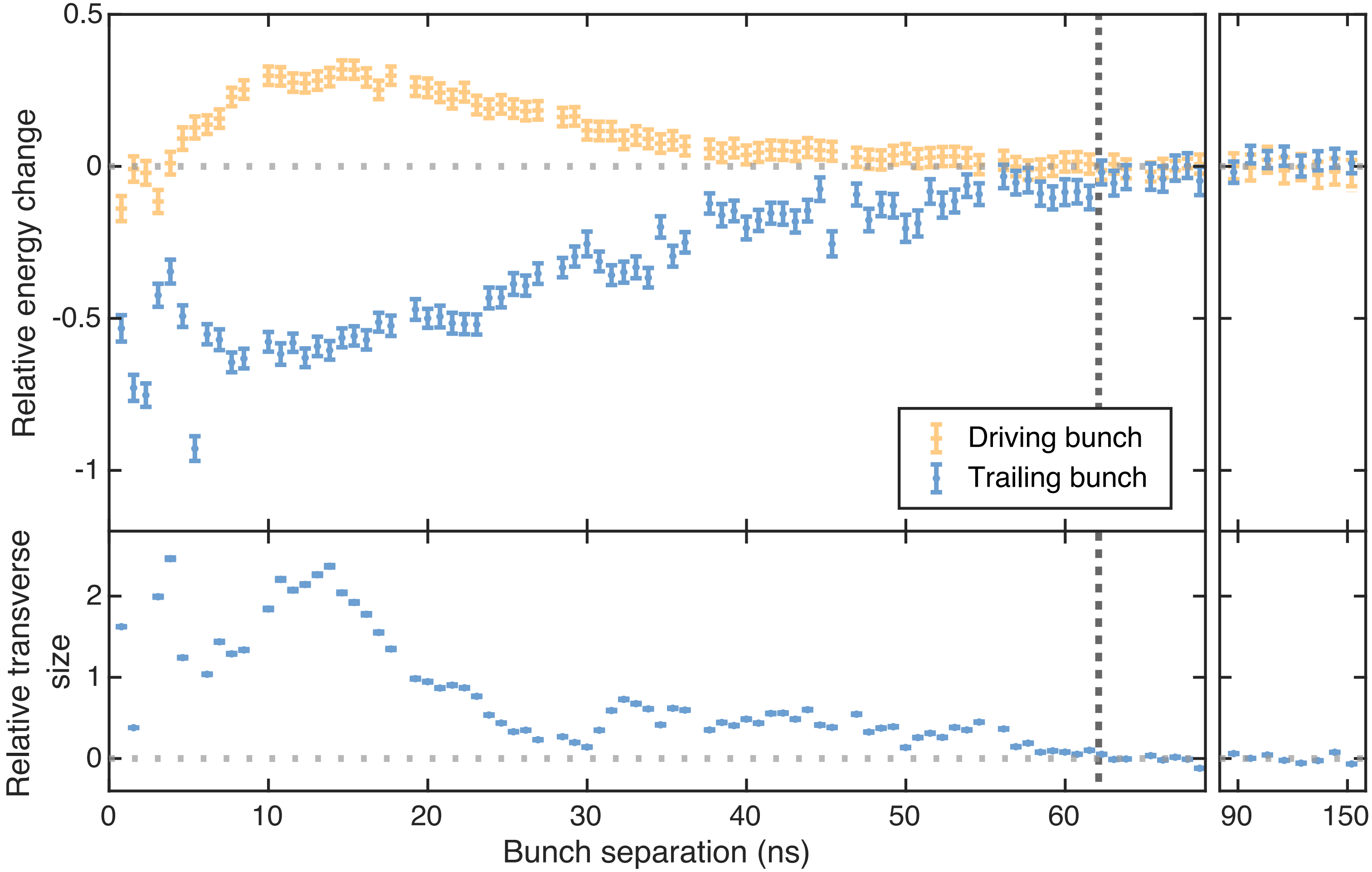
Basic L/PWFA limits - Rates



- A leading bunch perturbs the plasma by driving a wake
- A second probe-bunch pair arrives >0.77 ns behind the leading bunch and samples the plasma at that point in time
- The nature of the plasma can be inferred from the probe-bunch properties after driving its own wake
- The delay of the probe bunch can be changed in order to map out the evolution
- Analogous to pump-probe methodology in photon science

D'Arcy et al., Nature 603, 58–62 (2022)

Basic L/PWFA limits - Rates

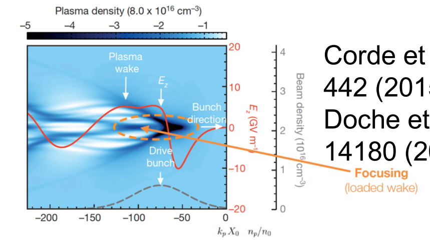


D'Arcy et al., Nature 603, 58–62 (2022)

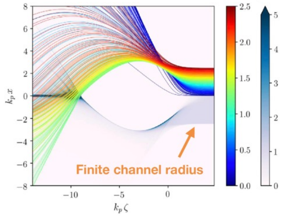
- Corresponds to rate limit ~ 16 MHz. NB – intrinsic limit due to physics processes – in practice, limit set by engineering issues, e.g. cell cooling, plasma generation…

Basic Limits – e+ acceleration

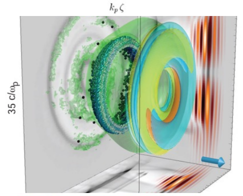
- Many approaches to e^+ acceleration:
- Linear wakefields: original observation of e^+ acceleration – but cannot escape from low efficiency, high emittance and low gradient;
- Non-linear wakefields – blow-out accelerating regime is naturally defocusing – basically need to manipulate beam or plasma:
  - **“self-loading” regime may work – but bunch shape distorts in equilibrium – likely to give high emittance;**
  - **Limit the diameter of the plasma cylinder – can give region of both acceleration & focusing. Promising, but potential sources of emittance growth need further investigation;**
  - **Wake inversion – tailor the beam shape e.g. torus can engineer blow-out – but beam loading gives non-linear focusing;**
  - **Hollow Channel – conjugate of WI – tailor plasma so no ions on axis to defocus e+ - but stability issues - may require strong focusing.**



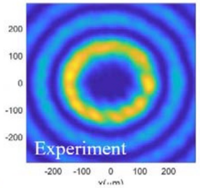
Corde et al., Nature 524, 442 (2015)
Doche et al., Sci. Rep. 7, 14180 (2017



Diederichs et al., PRAB 22, 081301 (2019)



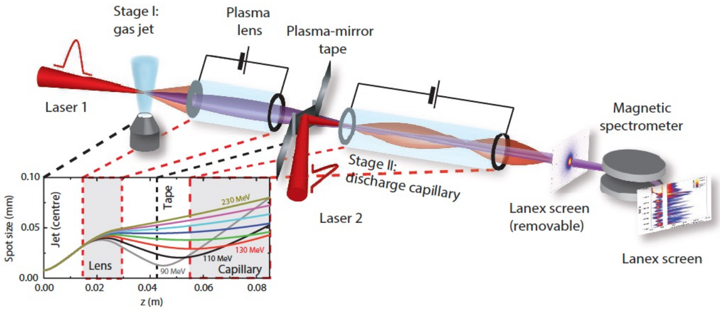
Viera & Mendonca, Phys.Rev. Lett 112 215001 (2014)
Vier et al., AIP Conf. Proc. 1777, 070112(2016)



Tajima, Proc. HEACC1983, 470 (1983)
Lee et al., Phys. Rev. E 64, 045501 (2001)

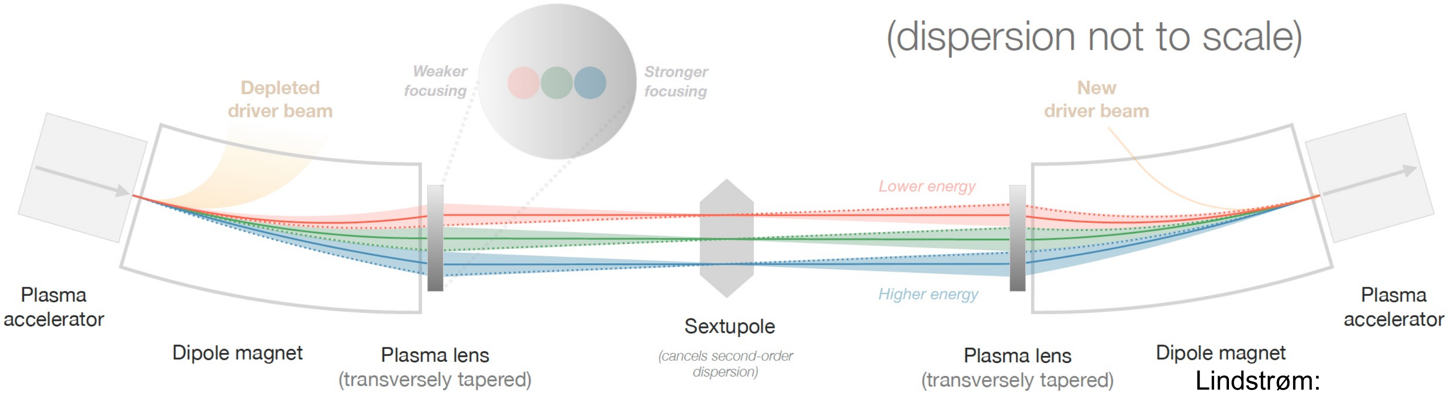
Basic Limits – Staging

- Staging demonstrated – but as yet no scheme that preserves emittance & charge.



Proof-of-principle demonstration of staging at LBNL.
Image source: Steinke et al., Nature 530, 190 (2016).

- Several new ideas, e.g. achromatic staging with non-linear plasma lenses



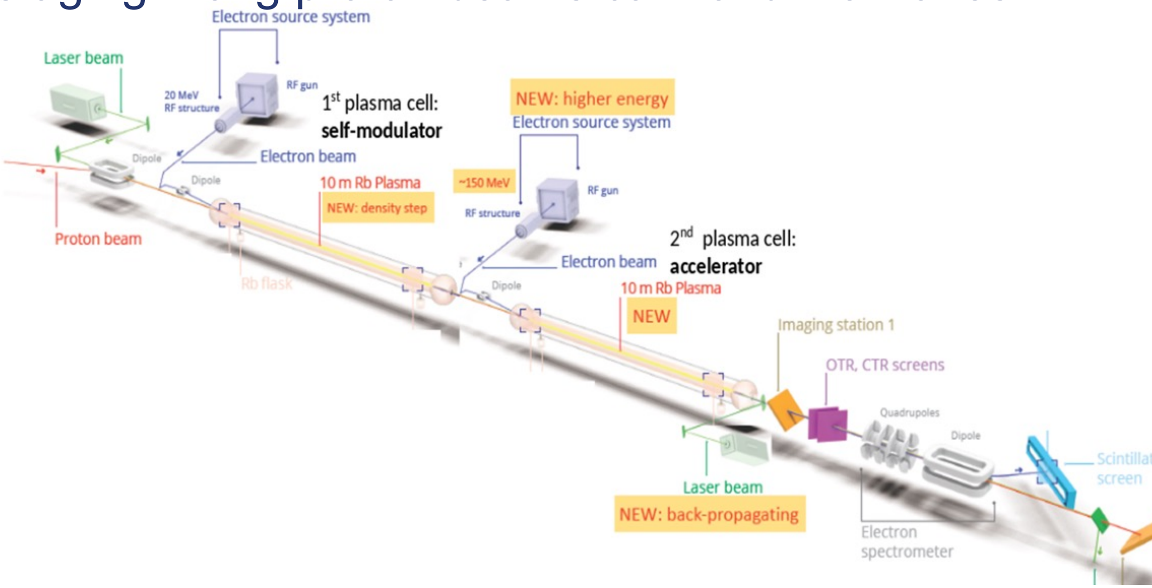
Lindstrøm:
Phys. Rev. Accel. Beams **24**, 014801 (2021)

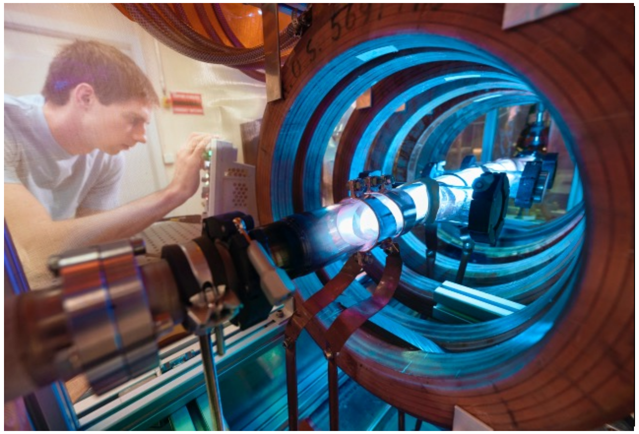
Outline

- **Introduction to Plasma Acceleration**
- **Applications to Colliders**
  - Injectors
  - Booster/afterburner
  - Stand-alone colliders
- **Summary**

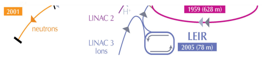
No Staging - AWAKE

- Proton-beam-driven facilitates long plasma cells and reduces/removes need for staging. Long proton beams cannot drive wakes.



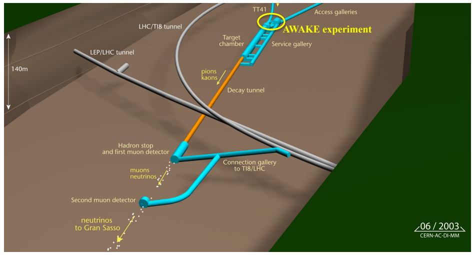


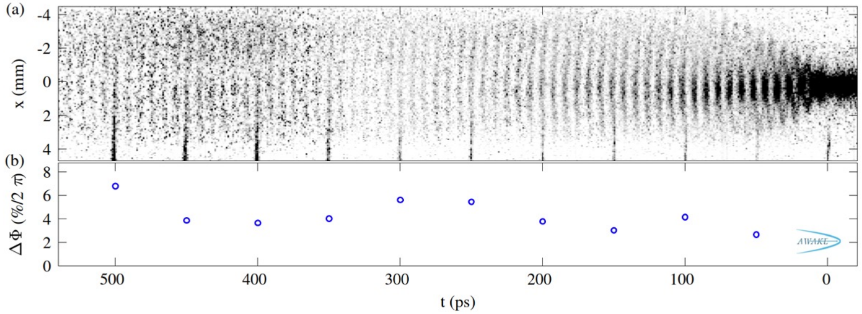
Plasma source 10m long, 4cm diameter, density $10^{14} – 10^{15}\mathrm{cm}^{-3}$



Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics

R Assmann et al.,
Plasma Physics and Controlled Fusion
Vol 56, Number 8





AWAKE Physics

- $\mathcal{L}$ Limited by p accelerator repetition rate – look for high-cross-section processes to compensate.

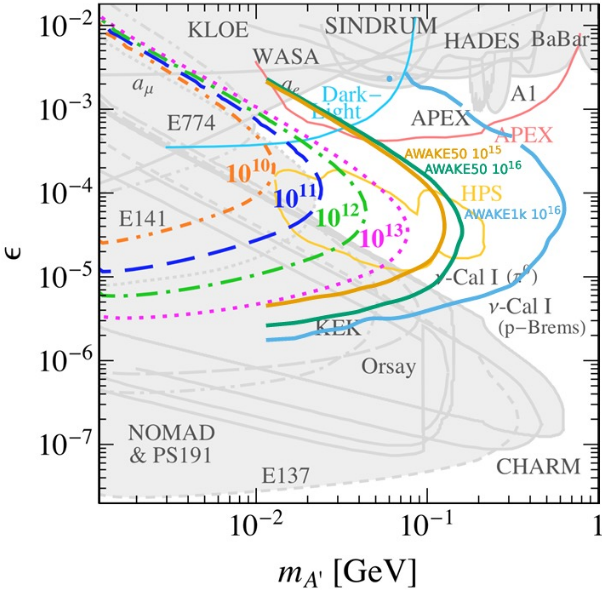
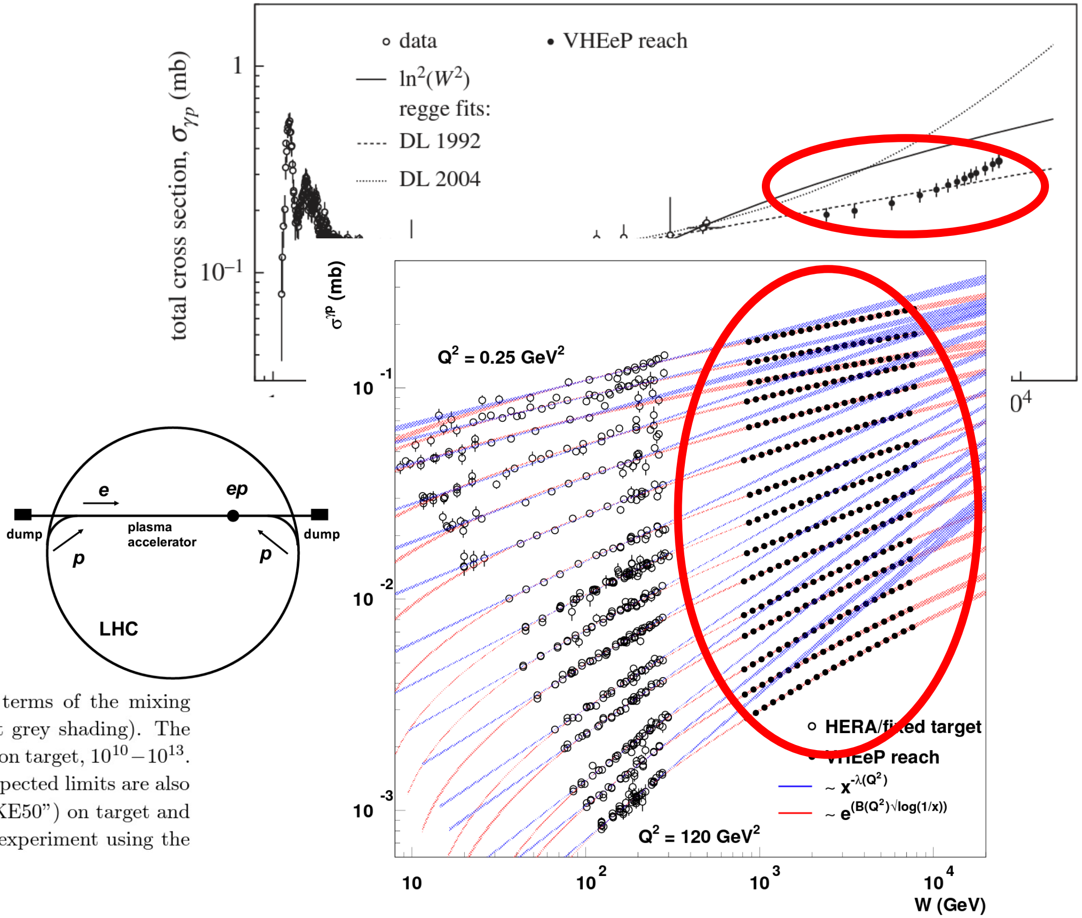


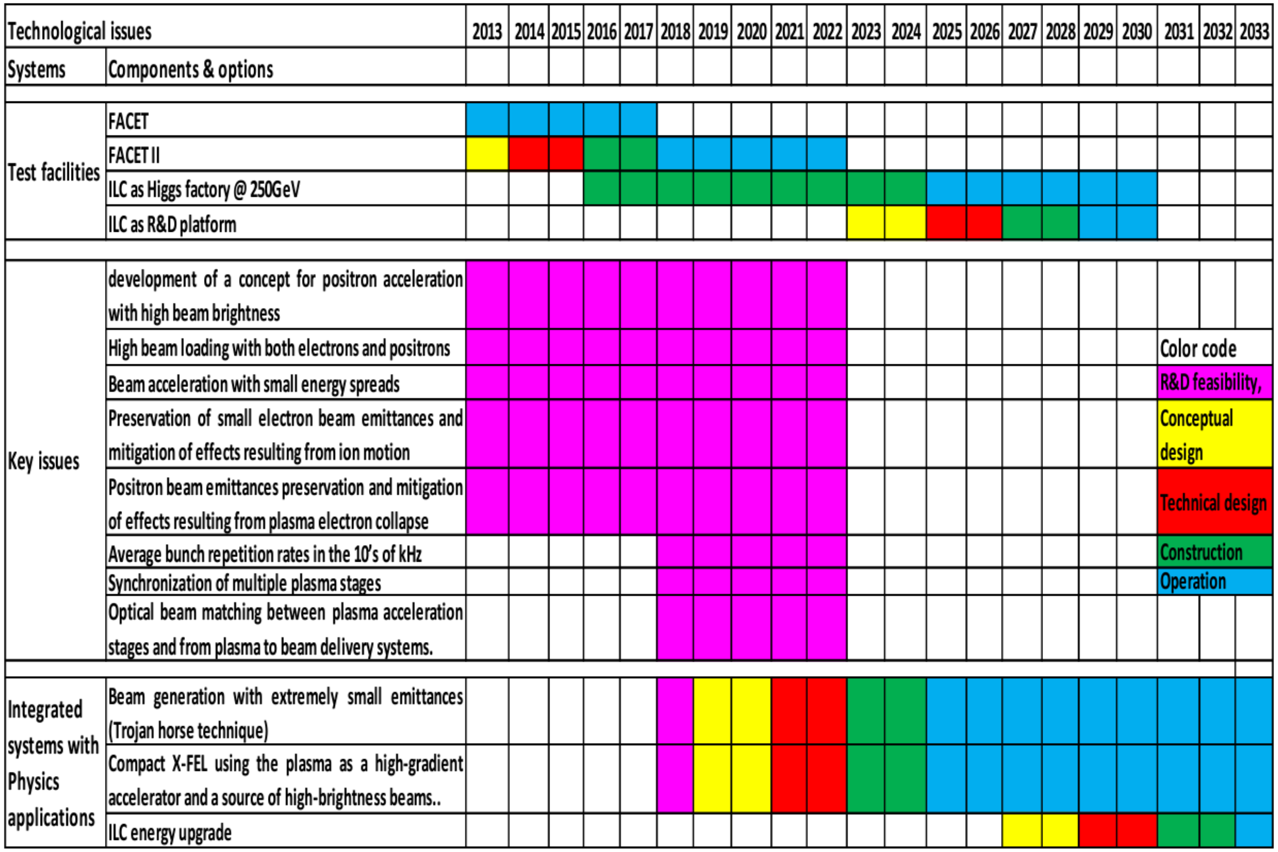
FIG. 8. Limits on dark photon production decaying to an e^+e^- pair in terms of the mixing strength, ϵ, and dark photon mass, $m_{A'}$, from previous measurements (light grey shading). The expected sensitivity for the NA64 experiment is shown for a range of electrons on target, $10^{10} - 10^{13}$. Expectations from other potential experiments are shown as colored lines. Expected limits are also shown for 10^{15} (orange line) or 10^{16} (green line) electrons of 50 GeV ("AWAKE50") on target and 10^{16} (blue line) electrons of 1 TeV ("AWAKE1k") on target provided to an experiment using the future AWAKE accelerator scheme. From Ref. [29].



L/PWFA Colliders

- Ideas around now for a long time.

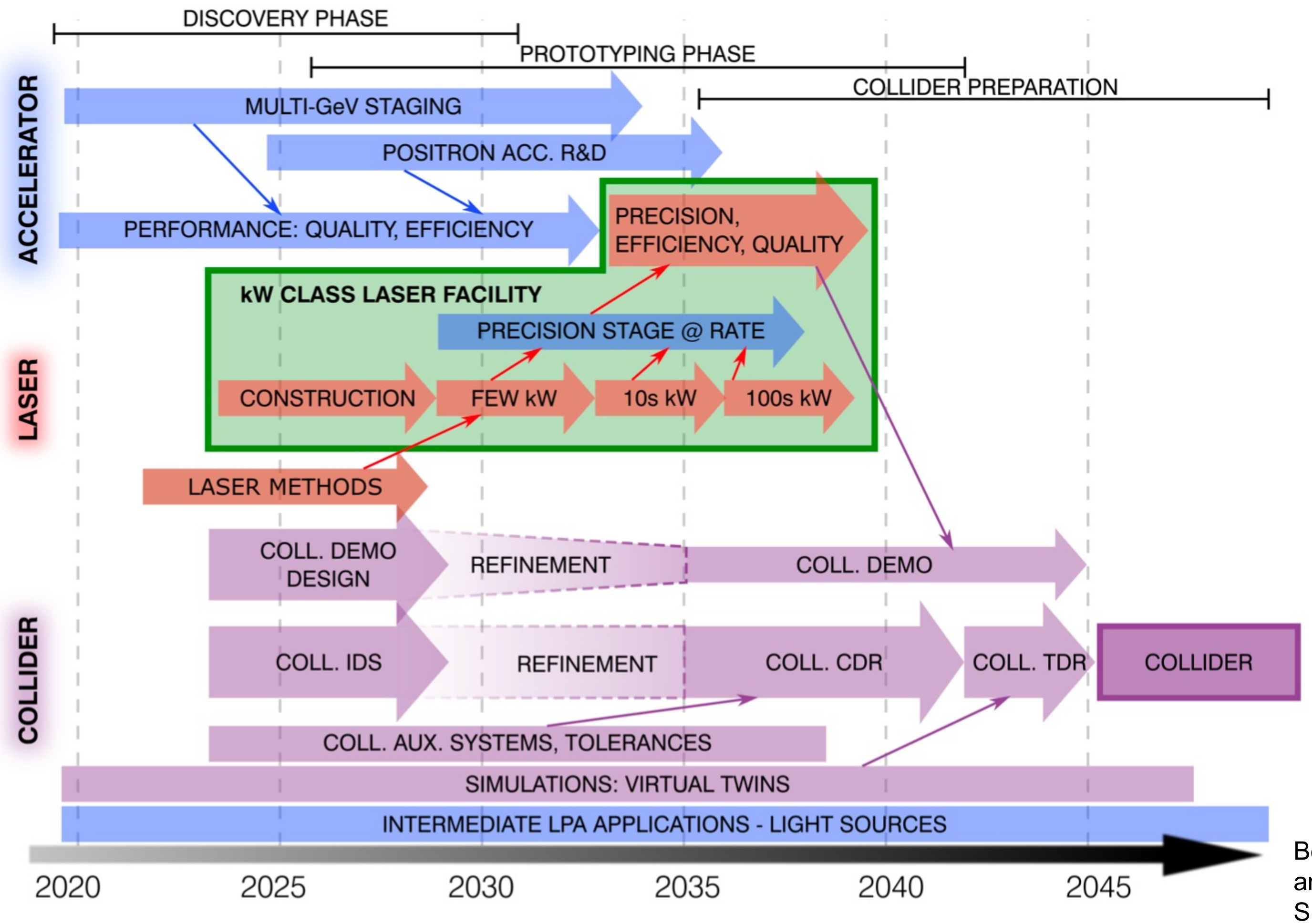
Figure 6: Tentative PWFA schedule for R&D and possible applications



Technological issues		2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Systems	Components & options																					
Test facilities	FACET	🟦	🟦	🟦	🟦	🟦																
	FACET II	🟨	🟥	🟥	🟩	🟩	🟦	🟦	🟦	🟦	🟦											
	ILC as Higgs factory @ 250GeV				🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦			
	ILC as R&D platform											🟨	🟨	🟥	🟥	🟩	🟩	🟦	🟦			
Key issues	development of a concept for positron acceleration with high beam brightness	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪											
	High beam loading with both electrons and positrons	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪									Color code		
	Beam acceleration with small energy spreads	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪									🟪 R&D feasibility,		
	Preservation of small electron beam emittances and mitigation of effects resulting from ion motion	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪									🟨 Conceptual design		
	Positron beam emittances preservation and mitigation of effects resulting from plasma electron collapse	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪									🟥 Technical design		
	Average bunch repetition rates in the 10's of kHz						🟪	🟪	🟪	🟪	🟪									🟩 Construction		
	Synchronization of multiple plasma stages						🟪	🟪	🟪	🟪	🟪									🟦 Operation		
	Optical beam matching between plasma acceleration stages and from plasma to beam delivery systems.						🟪	🟪	🟪	🟪	🟪											
Integrated systems with Physics applications	Beam generation with extremely small emittances (Trojan horse technique)						🟪	🟨	🟨	🟥	🟥	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Compact X-FEL using the plasma as a high-gradient accelerator and a source of high-brightness beams..						🟪	🟨	🟨	🟥	🟥	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	ILC energy upgrade															🟨	🟨	🟥	🟥	🟩	🟩	🟦

Adli et al.,
arXiv: 1308.1145

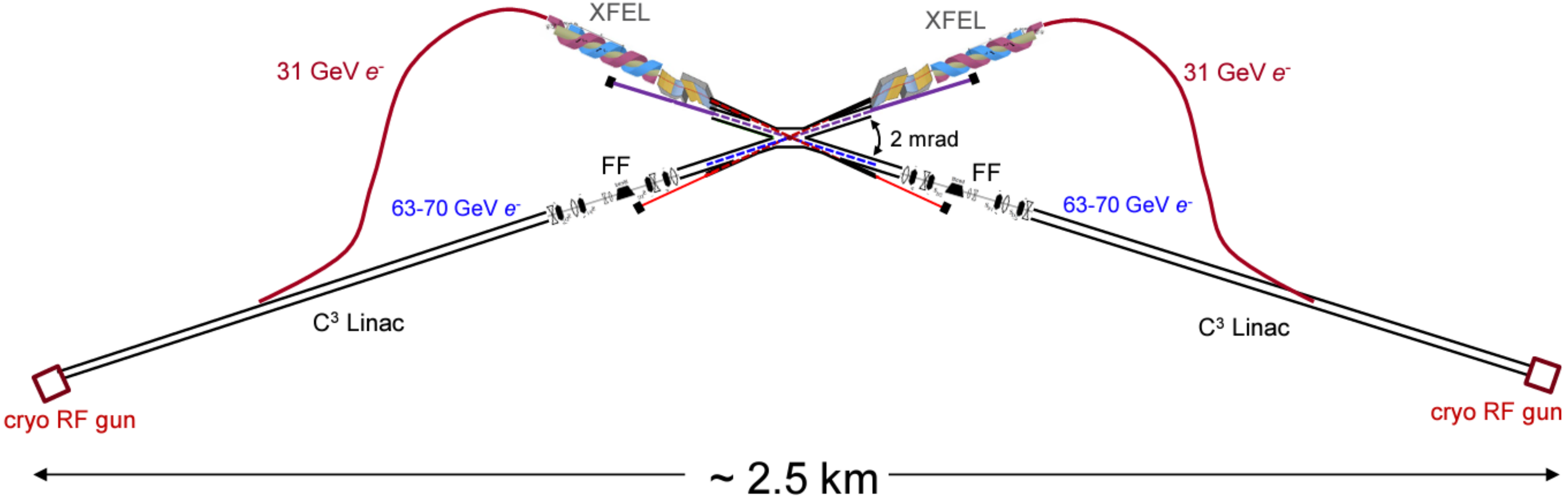
LWFA Colliders



Benedetti et al., arXiv:2203.08366 – Snowmass21 contribution

FIG. 2. Technically-limited high-level laser-plasma-accelerator-based collider R&D roadmap.

X-ray FEL-based γγ Collider Higgs Factory



Technology is C^3 @ 70 MV/m

Round beams may increase experimental backgrounds;

Beta functions highly challenging - tolerances!

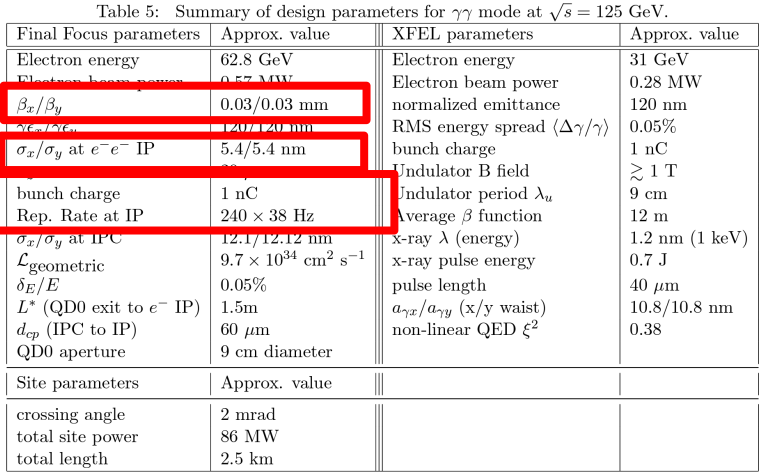


Table 5: Summary of design parameters for $\gamma\gamma$ mode at $\sqrt{s} = 125$ GeV.

Final Focus parameters	Approx. value	XFEL parameters	Approx. value
Electron energy	62.8 GeV	Electron energy	31 GeV
Electron beam power	0.57 MW	Electron beam power	0.28 MW
β_x/β_y	0.03/0.03 mm	normalized emittance	120 nm
$\gamma\epsilon_x/\gamma\epsilon_y$	120/120 nm	RMS energy spread $\langle\Delta\gamma/\gamma\rangle$	0.05%
σ_x/σ_y at e^-e^- IP	5.4/5.4 nm	bunch charge	1 nC
[illegible]	[illegible]	Undulator B field	$\gtrsim 1$ T
bunch charge	1 nC	Undulator period λ_u	9 cm
Rep. Rate at IP	240 × 38 Hz	Average β function	12 m
σ_x/σ_y at IPC	12.1/12.12 nm	x-ray λ (energy)	1.2 nm (1 keV)
$\mathcal{L}_{\text{geometric}}$	9.7×10^{34} cm^2 s^{-1}	x-ray pulse energy	0.7 J
δ_E/E	0.05%	pulse length	40 μm
L^* (QD0 exit to e^- IP)	1.5m	$a_{\gamma x}/a_{\gamma y}$ (x/y waist)	10.8/10.8 nm
d_{cp} (IPC to IP)	60 μm	non-linear QED ξ^2	0.38
QD0 aperture	9 cm diameter		

Site parameters	Approx. value		
crossing angle	2 mrad		
total site power	86 MW		
total length	2.5 km		

Barklow et al, arXiv:2203.08484 Snowmass21
See also
Barzi et al, arXiv:2203.08353 Snowmass21;
Adli, JINST 17 (2022) 05, T05006

Application Readiness

Application	**LWFA**	**PWFA**	**DWFA**	**DLA**	**Cyro NCRF**
Light sources	Near to mid	Near to mid	Near	Mid to long	Near
HEP add-ons	Near to mid	Near to mid	Near	Unknown	Near
e- only HEP	Mid to long	Mid to long	Near to mid	Unknown	Near
Multi-TeV ALIC	Long	Long	Mid	Unknown	Near to Mid
10-TeV ALIC	Longer	Longer	Not suitable	Unknown	Not suitable

Carlston et al,
J. Phys.1596 (2020) 012063

Asymmetric Hybrid Higgs Factory

Another way to avoid the e^+ problem - use conventional technology and reduce cost by reducing energy. Obviously, this boosts the collision frame.

Some simple relativistic kinematics:

E_{cm}= 2sqrt(E_1E_2); gamma = (E_1+E_2)/E_{cm}

For HERA, γ of CM was (27.5+920)/318 = ~3

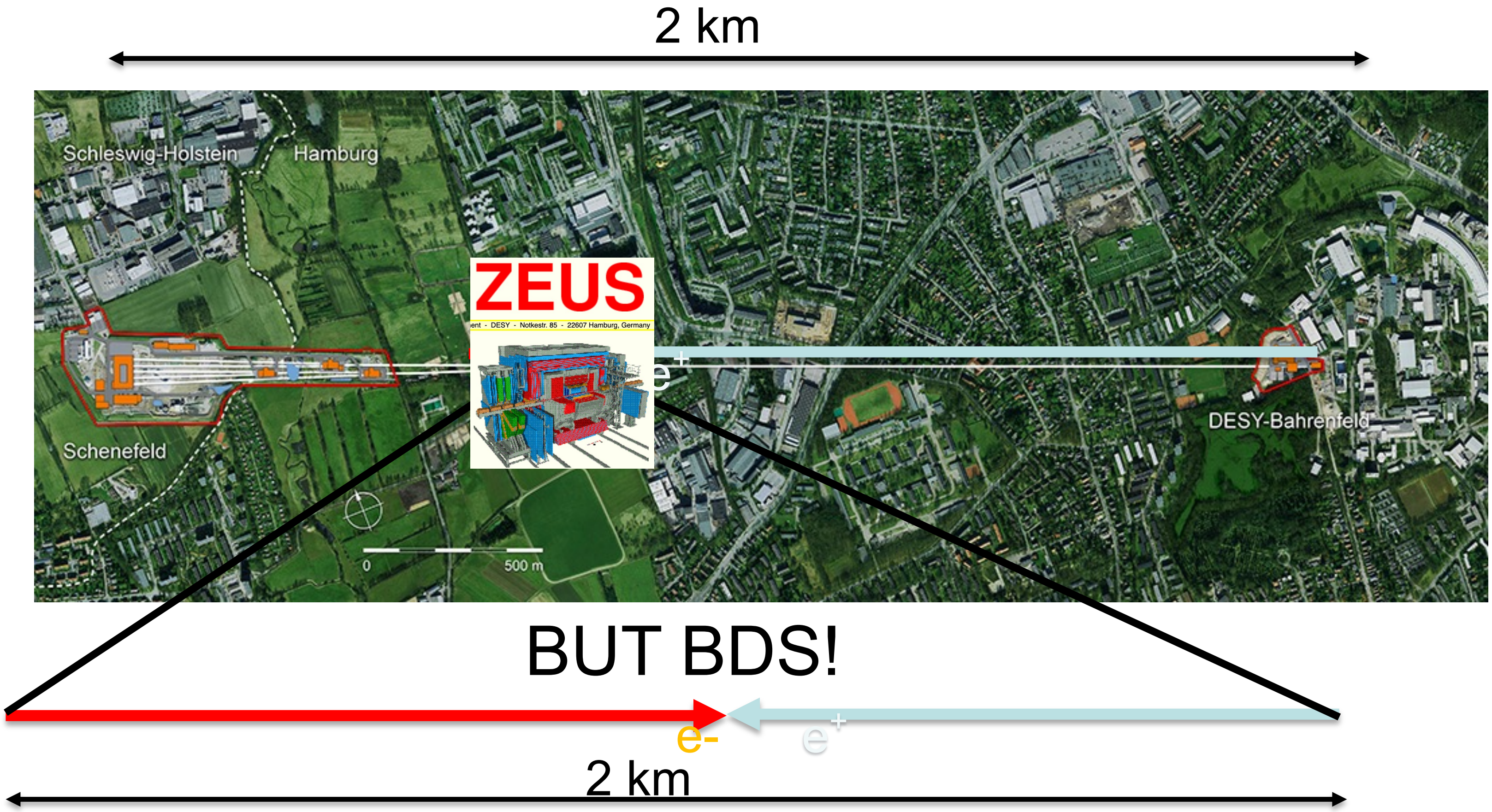
For an e^+e^- Higgs factory assume E_{cm} =125 GeV; for same γ as Hera,

E_1E_2 = 125*125/4 and E_1+E_2 = 3*125, which has solution for roughly

E_1 ~ 10.7 GeV, E_2 ~ 364.3 GeV.

Asymmetric Hybrid Higgs Factory (A HH Factory)

Why not use E-XFEL, with added e^+ source @ 17.5 GeV? For E_{cm} =125 GeV, E_{e-} ~223 GeV => γ ~ 2. Assuming 1 GV/m PWFA then:



BUT BDS!

Summary & Outlook

1) Many promises made on the applications of L/PWFA to pp. Progress but so far no application in the real world. Realistic timescales essential.
2) Afterburners etc. have to accept beam parameters from conventional machines. Proper proposal for PWFA collider needs to start from *tabula rasa* to optimise bunch numbers & structure, currents etc. Shorten BDS – plasma lenses?
3) 24/7 reliability & weeks of stable operation required.
4) High power/repetition rate/efficiency
5) Positrons. Some distance from a solution that could be applied to a real machine. R&D @ FACET-II
6) Maybe hybrid solutions – either with conventional or structure acceleration – or $\gamma\gamma$ - are a way forward?
7) Non-pp PWFA application much closer – eventually progress here will also feed through to pp.