10 TeV Wakefield Collider Design Study
~~ LWFA linac WG kick-off meeting ~~

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U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Revisiting the motivations and goals of the 10 TeV Collider Design Study
- Scope of LWFA linac WG and synergies with other WGs
- Preliminary considerations for the design of a multi-TeV LWFA linac (for e+/e-, e-/e-, gamma-gamma)
- Next steps (e.g., future tasks, input for ESPP)
- Discussion

P5 report recommends effort towards development of 10 TeV pCM collider and encourages development of self-consistent design for a wakefield-based collider.

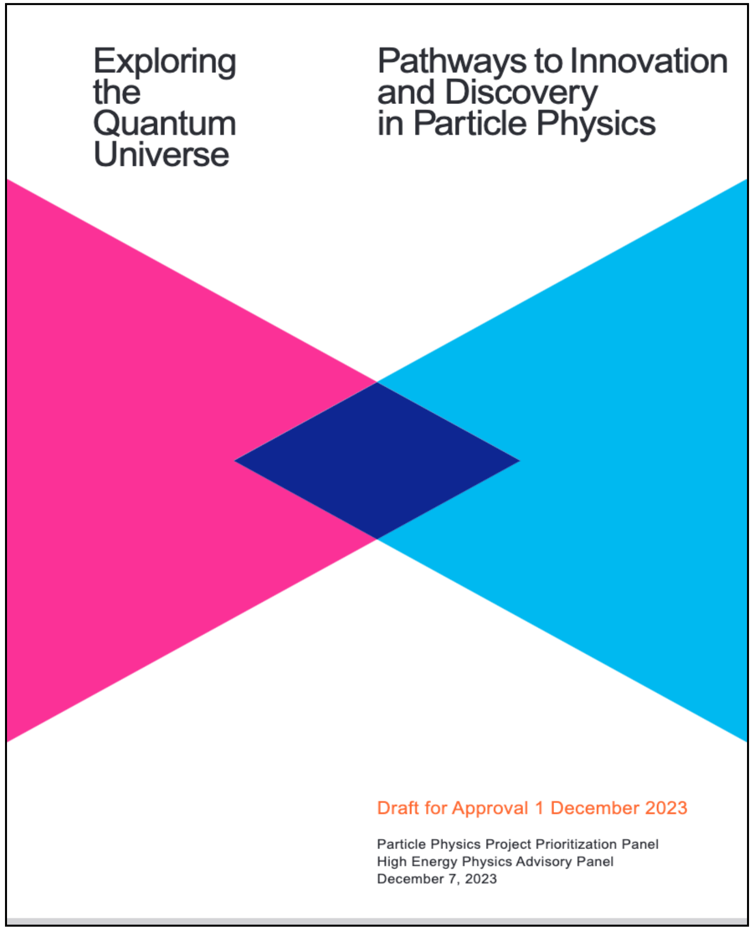
"Recommendation 4: **Support** a comprehensive **effort** to develop the resources - theoretical, computational, and technological — essential to our 20-year vision for the field. This includes an **aggressive R&D program** that, while technologically challenging, could yield revolutionary accelerator designs that **chart a realistic path to a 10 TeV pCM collider**."

"Parallel to the R&D for a Higgs factory, **the US R&D effort should develop a 10 TeV pCM collider**, such as a muon collider, a proton collider, or **possibly** an electron-positron collider **based on wakefield** technology."

"Wakefield concepts for a collider are in the early stages of development → critical next step is the delivery of an end-to-end design concept, including cost scales, **with self-consistent parameters** throughout."

10 TeV pCM Wakefield Collider Design Study Group established

S. Gessner's full introduction from AAC'24
https://indico.fnal.gov/event/59618/contributions/294346/



https://www.usparticlephysics.org/2023-p5-report/

Goals and timeline of the 10 TeV pCM Wakefield Collider Design Study

Goals

- **Deliver self-consistent set of beam parameters;**
- **End-to-end design (with reduced models when possible);**
- **Consider environmental impact in the design.**

→ Keep close connections with HEP theorists and experimentalists to define physics program (which might affect beam parameters);
→ Use a community-driven approach;
→ Collaboration w/ on-going LC design efforts (e.g., ALEGRO, HALHF) is welcome.

Timeline

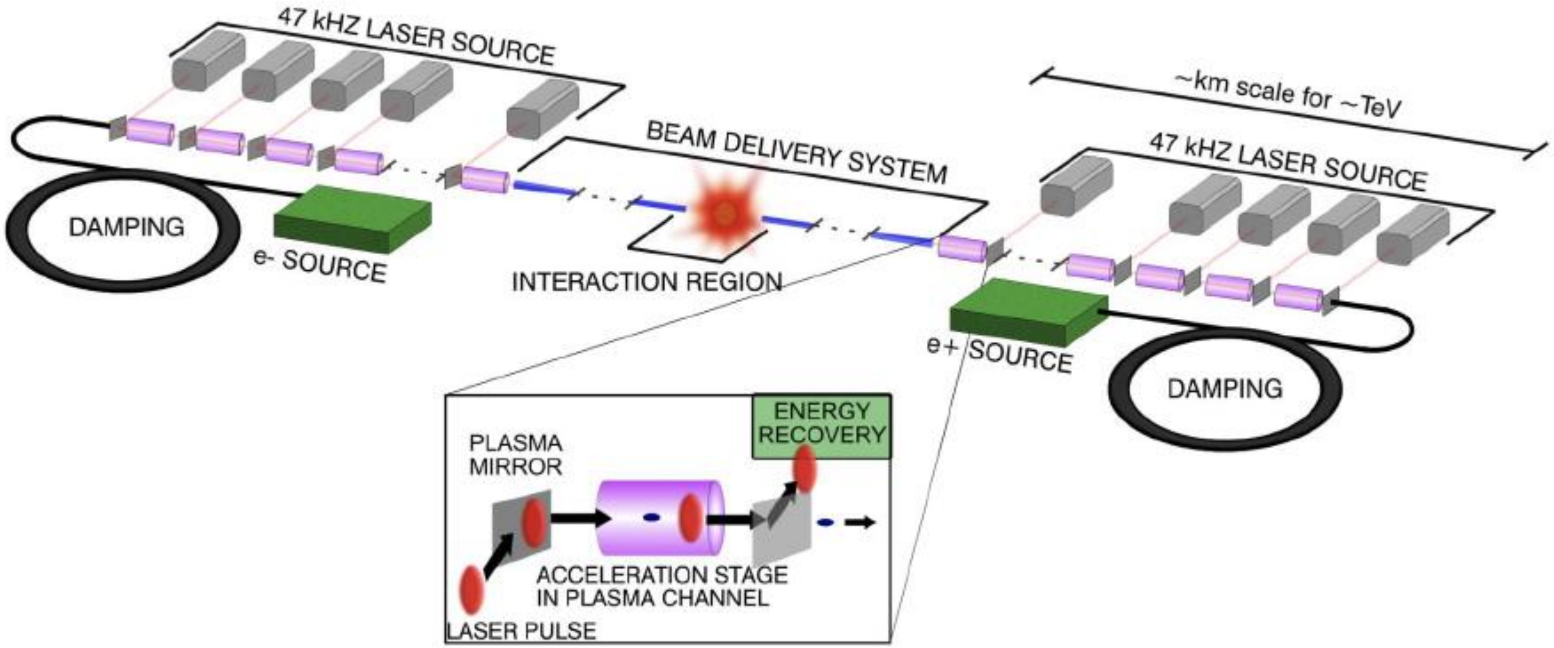
Ongoing	1 year	2 year	3 year	4 year
Study organization.	Unified study of SWFA/PWFA/LWFA for electron arm of linac	Review tech options and converge on accelerator concepts.	Collaboration on designs and self-consistent parameters.	End-to-end design study report due sometime in 2028.
Solicit input from HEP physicists on e^+e^-, e^-e^-, $\gamma\gamma$ collisions.	Intensify engagement on "traditional systems" and begin work on BDS, sources, etc	Review options and converge on HEP collider type (e^+e^-, e^-e^-, $\gamma\gamma$)	Identification of required R&D and demo facilities	
Provide community input for the next ESPP, March 2025	Intensify engagement with HEP on detectors			

Gessner, AAC'24

The Collider Design Study is organized into WGs

- System integration and optimization
- Beam sources (incl. damping rings)
- Drivers
  - Laser
  - Beams - SWFA
  - Beams - PWFA
- Linacs
  - LWFA
  - SWFA
  - PWFA
- Beam delivery system
- Beam-beam interactions
- Beam diagnostics
- Machine-detector interface
- HEP detector
- HEP physics case
- Environmental impact
- Simulations/computing/AI

This is us!



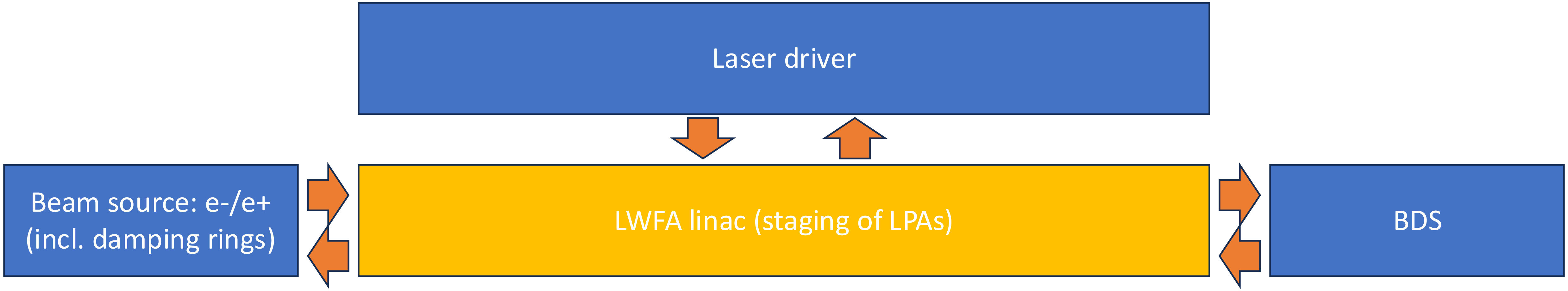
Green = Broader accelerator community

Orange/blue/purple = AAC specific

Red = HEP and broader community

Gessner, AAC'24

Scope of LWFA linac WG (and synergies with other WGs)



LWFA linac WG:

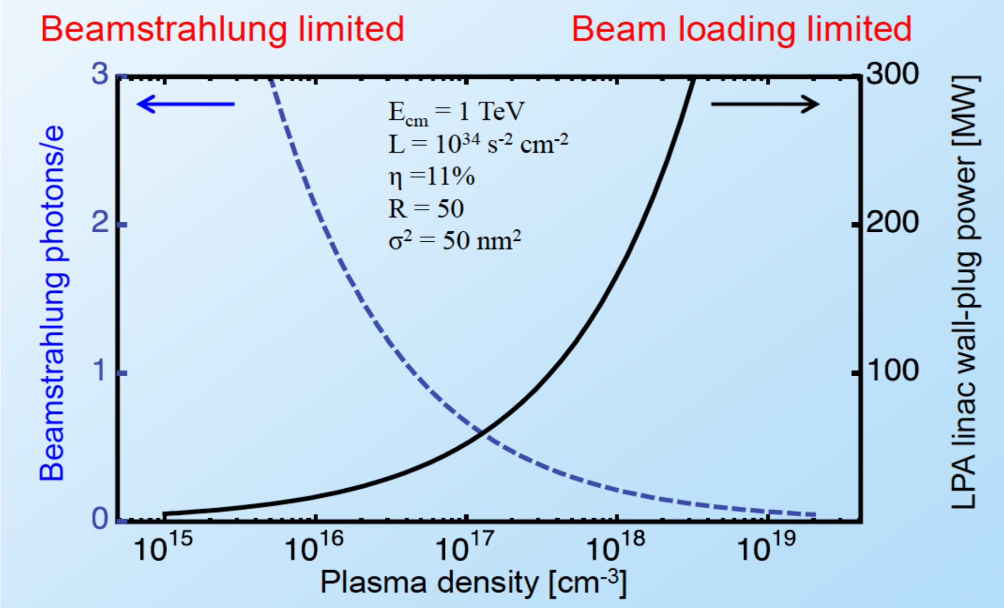
- Accelerate "acceptable electron (and positron) beams" from the beam source to the BDS in a compact and cost-effective manner

  "acceptable beams" → determined as <u>compromise</u> between source, BDS, laser driver, and linac capabilities

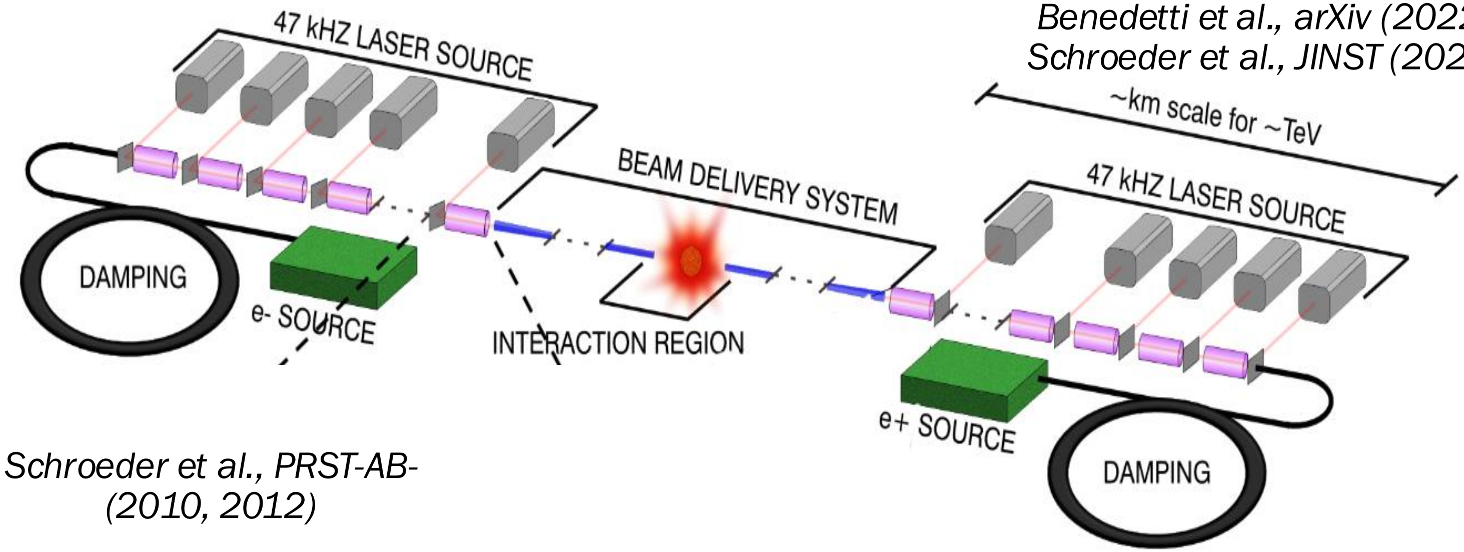
- Identify key challenges (e.g., quality-preserving staging, positrons, etc.)
- Perform reviews of different technologies (i.e., what LWFA regime? What type of inter-stage transport?)
- Develop metrics* (i.e., how well does a given technology perform?)
  - Evaluate maturity of technology
  - Maximize acceptable particles delivered to BDS / Power consumption
  - Minimize linac footprint (cost)
  - …..

* Same as metrics for PWFA linac

Preliminary LWFA and bunch parameters determined from scaling laws by minimization of wall-plug power and beamstrahlung



Benedetti et al., arXiv (2022)
Schroeder et al., JINST (2023)



Schroeder et al., PRST-AB- (2010, 2012)

LWFA properties determined by minimization of wall-plug power, linac length, and beamstrahlung + achieve desired luminosity (~10^{34} cm^{-2} s^{-1}):

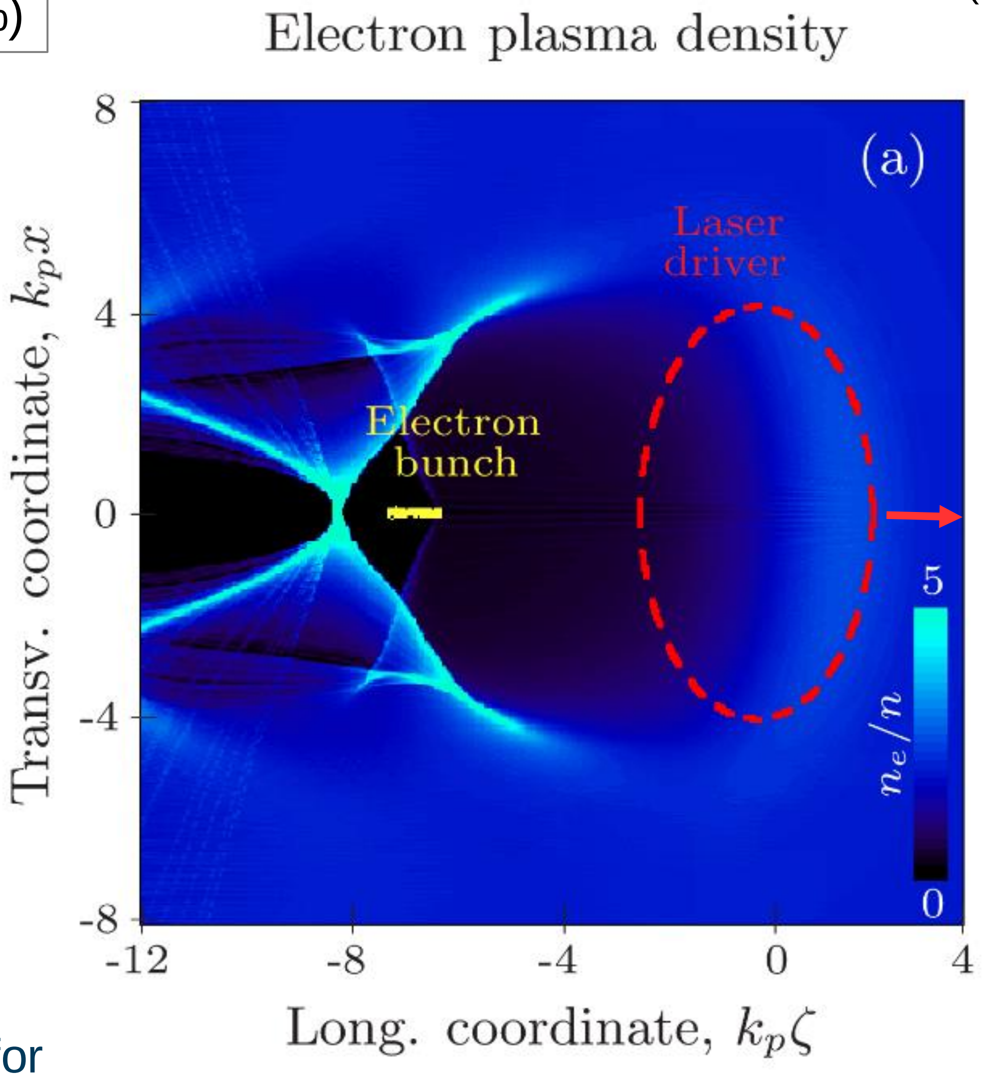
- n_0~10^{17} cm^{-3} → 10s of J laser / stage
- multi-GeV energy gain / stage
- high bunch charge (>100s pC)
- high bunch quality (emittance < 0.1 um, energy spread < 1%)
- high efficiency (10s %, laser → wake, wake → beam, …)
- ~100s LPA stages/TeV

Example of LWFA stage operating in the bubble regime providing high-gradient, high-charge, and high-efficiency

Laser: U=50 J, λ_0=1.0 μm, a_0=4.5, T_0=80 fs, w_0=36 μm
Plasma: n_0= 3.4x10^{17} cm^{-3}, stage length = 3.1 cm, linear taper (+74%)

Schroeder et al., JINST (2022)

ΔW_{bunch}= 3.08 GeV (100 GV/m)
Q_{bunch}= 1.3 nC – L_{bunch} =9.3 μm – I_{bunch} =49 kA
Energy spread = 0.1% (with shaped bunch current)



Energy considerations:

- Wake-to-bunch energy transfer = 40%
- Laser driver depletion = 20% → remaining laser driver energy could be returned to the grid with photovoltaic

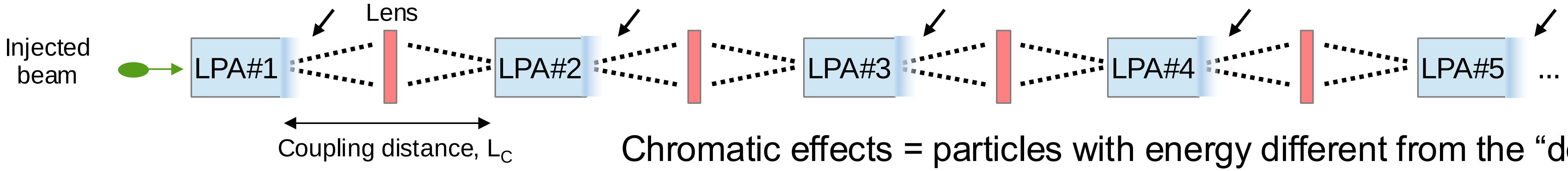
→ ~320 LPA stages/TeV

→ Stable (w/ ion motion) + no emittance growth from Coulomb scattering + negligible synchrotron radiation-induced energy spread

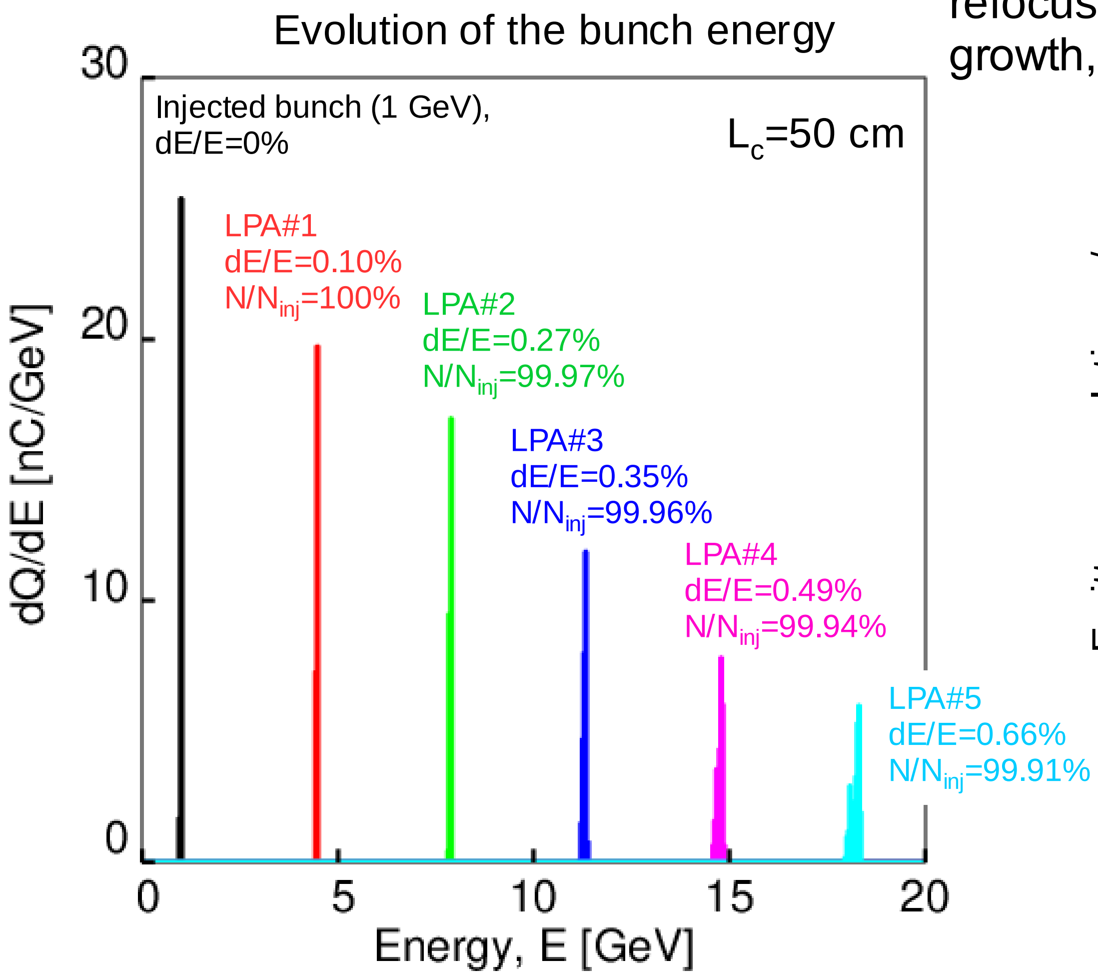
→ Not suitable for positrons

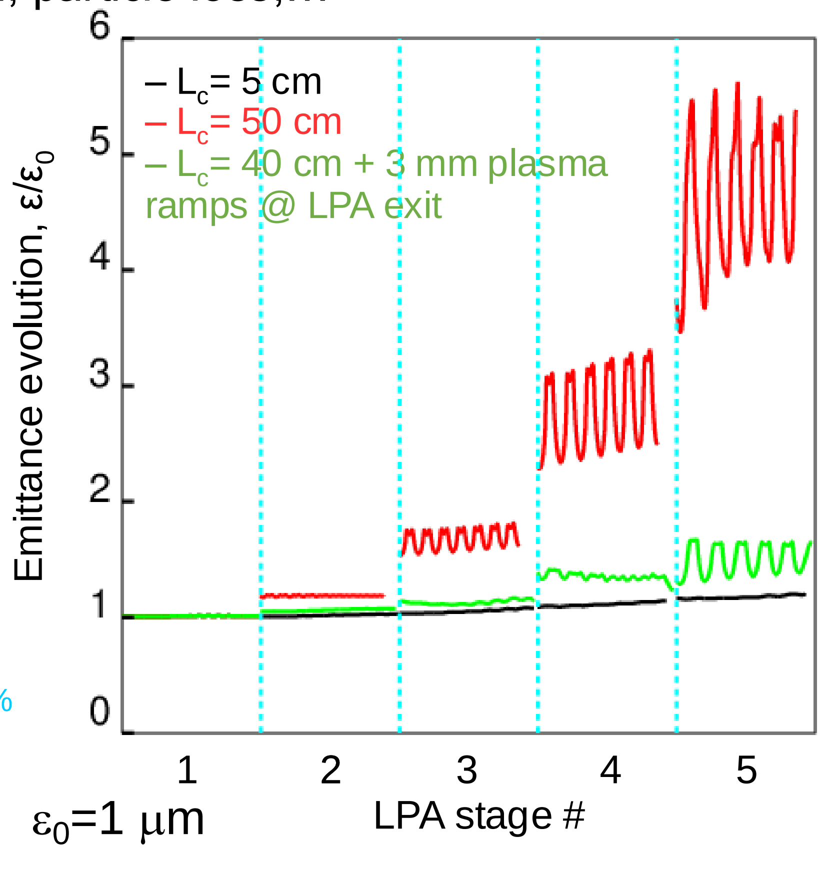
→ Strong focusing yields small bunch size (~nm @ ~ TeV energies for collider-relevant emittances): **challenging for inter-stage transport and alignment!**

Emittance preservation requires development of achromatic inter-stage transport elements for e-beam



Chromatic effects = particles with energy different from the "design" value are refocused at incorrect transverse location: mismatch, additional emittance growth, particle loss,…





ε_0=1 μm

Emittance growth from chromaticity in drifts:

$$\Delta\varepsilon \simeq \left(\frac{\varepsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\frac{s}{\gamma_0}$$

Exit ramp expands beam size preserving emittance (if $k_\beta L_{ramp} \gtrsim 1$): ε_0/σ_0 **decreases!**

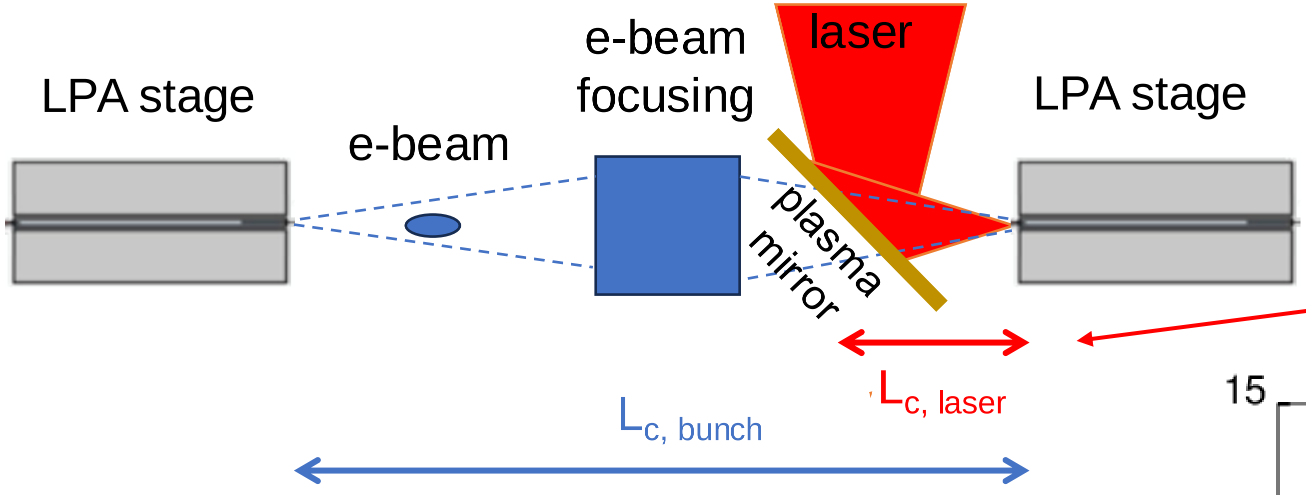
Migliorati et al., PRAB (2013)
Thomas and Seipt, PRAB (2022)

- Ramps become (too) long at high energy
- Development of achromatic focusing optics (or with large chromatic acceptance) required

C. Lindstroem, PRAB (2021)

→ compactness challenging!

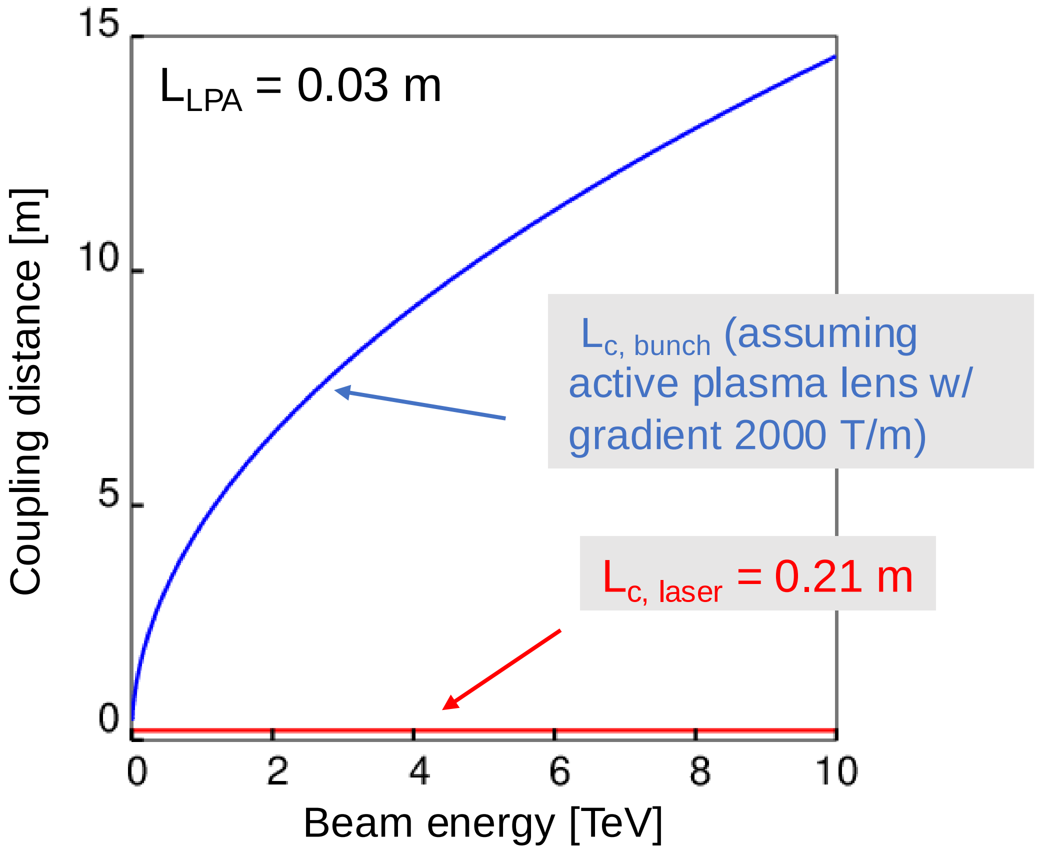
Minimum coupling distance between stages determined by refocusing of tightly-focused bunch (not laser in-coupling)



Determined by laser intensity @ plasma mirror (I_{pm}~10^{16} W/cm^2)

Determined by focusing gradient (~ fixed to its max value) and beam energy

→ $L_{c,\ bunch} \sim \gamma^{1/2}$



→ Average gradient decreases with energy (LPA stages are further and further apart)

→ Focusing optics always needed for tightly focused bunches (ballistic transport possible above >44 TeV)

Example of LWFA-based gamma-gamma collider parameters developed to guide R&D

Starting point for future studies!

Laser driver parameters

Laser pulse energy	50 J
Laser (FWHM intensity) pulse duration	70 fs
Laser spot size	31 μm
Laser strength parameter, a_0	4.5
Laser pulse peak power	0.43 PW
Laser wavelength	0.8 μm
Plasma density	4.6×10^{17} cm^{-3}
Plasma cell length	3.1 cm
Bunch charge	1.2 nC
Bunch number	7.5×10^{9}
RMS beam length	2.2 μm
Loaded accelerating gradient	117 GV/m
Particle energy gain per stage	3.2 GeV

Machine and particle beam parameters

Center-of-mass photon energy	15 TeV
Photon beam energy	7.5 TeV
Electron beam energy	9.1 TeV
Beam power	12.5 MW
Repetition rate	1.1 kHz
Time between collisions	0.9 ms
Vertical beam emittance	100 nm
Horizontal beam emittance	100 nm
Final focus beta functions, $\beta_x^* = \beta_y^*$	0.15 mm
Scattering wavelength	36 μm
Geometric luminosity	2×10^{35} cm^{-2} s^{-1}
Facility site power (2 linacs)	415 MW

Schroeder *et al.*, JINST 18 T06001 (2023)

Example of LWFA stage operating in the quasi-linear regime providing high-gradient, high-charge, and high-efficiency

Laser: U=8.9 J, λ_0=1.0 um, a_0=1.8, T_0=73 fs , w_0=41 μm
Plasma (hollow channel): n_0=0.96x10^{17} cm^{-3}, R_c=24 μm, stage length = 78 cm w/ optimal taper

Schroeder et al., NIMA (2016)

ΔW_{bunch}= 5.05 GeV (6.5 GV/m)
Q_{bunch}= 0.24 nC – L_{bunch}=30 μm – I_{bunch} =5 kA
Energy spread = 0.8% (with shaped bunch current)

Energy considerations:

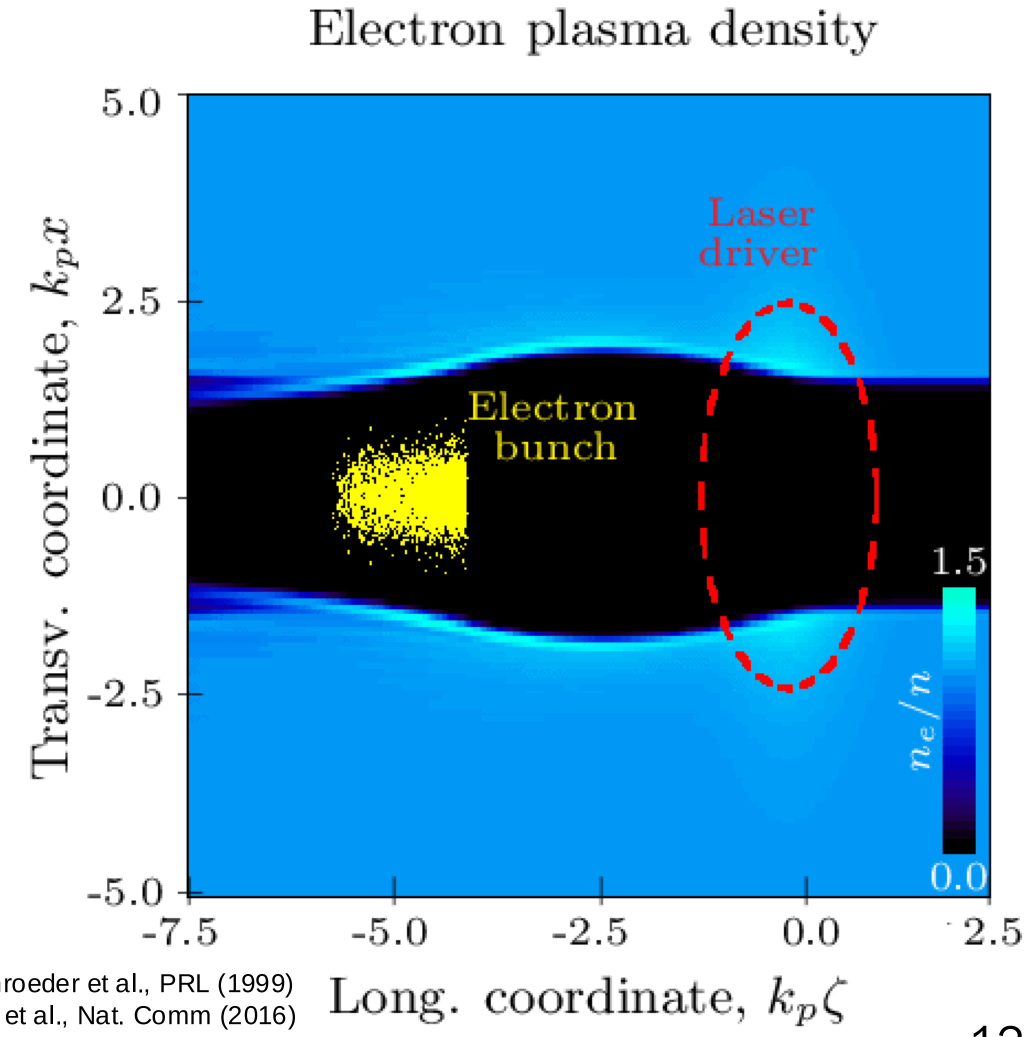
- Wake-to-bunch energy transfer = 68%
- Laser driver depletion = 20% → remaining laser driver energy could be returned to the grid with photovoltaic

→ ~200 LPA stages/TeV

→ Negligible emittance growth from Coulomb scattering + no energy spread from synchrotron radiation + suitable for positrons

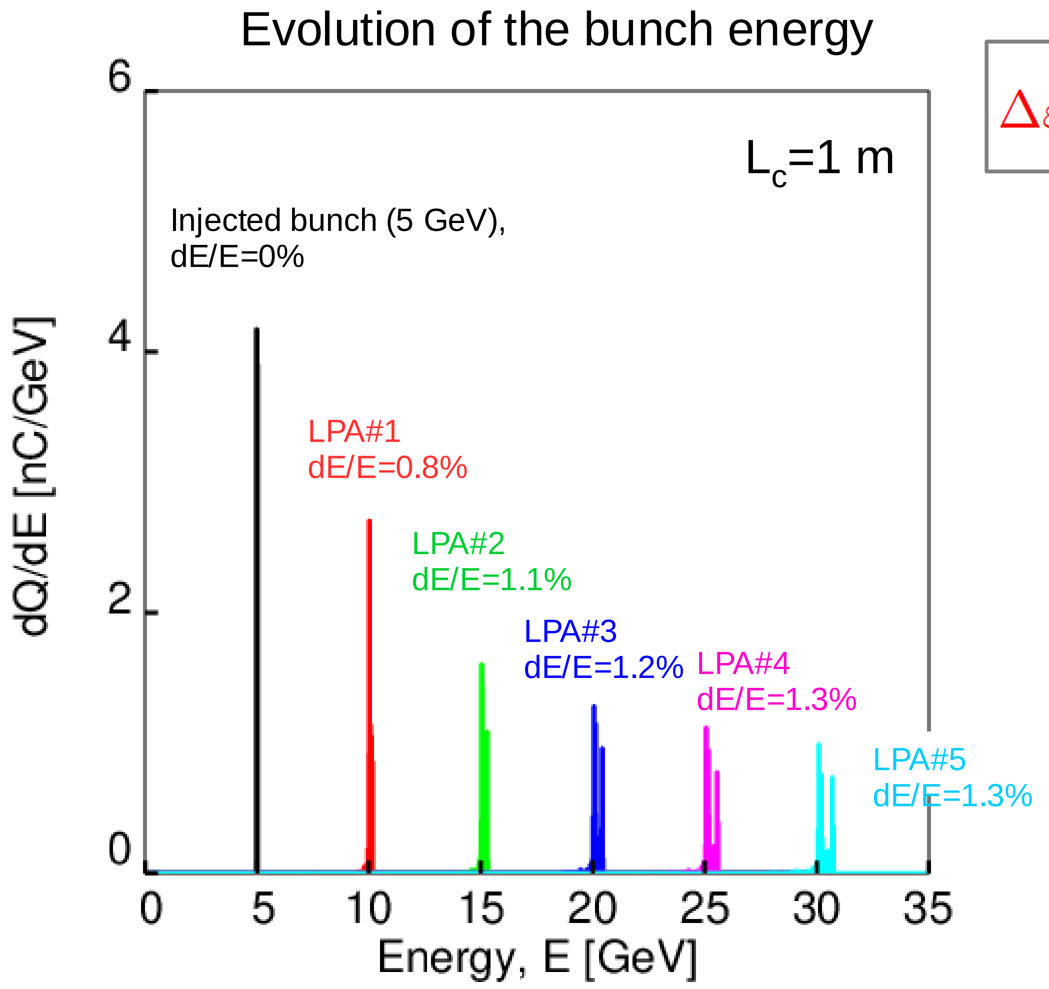
→ Unstable w/o strong focusing: potential stabilization mechanisms are currently being investigated

→ Hollow-channel allows for large (~um-scale) beam size: **relaxed constraints on inter-stage transport and alignment!**



Schroeder et al., PRL (1999)
Gessner et al., Nat. Comm (2016)
Lindstrøm et al., PRL (2018)

Use of large bunch sizes (enabled by hollow channel) results in suppression of chromatic emittance growth, relaxes alignment tolerances, and enables compact staging

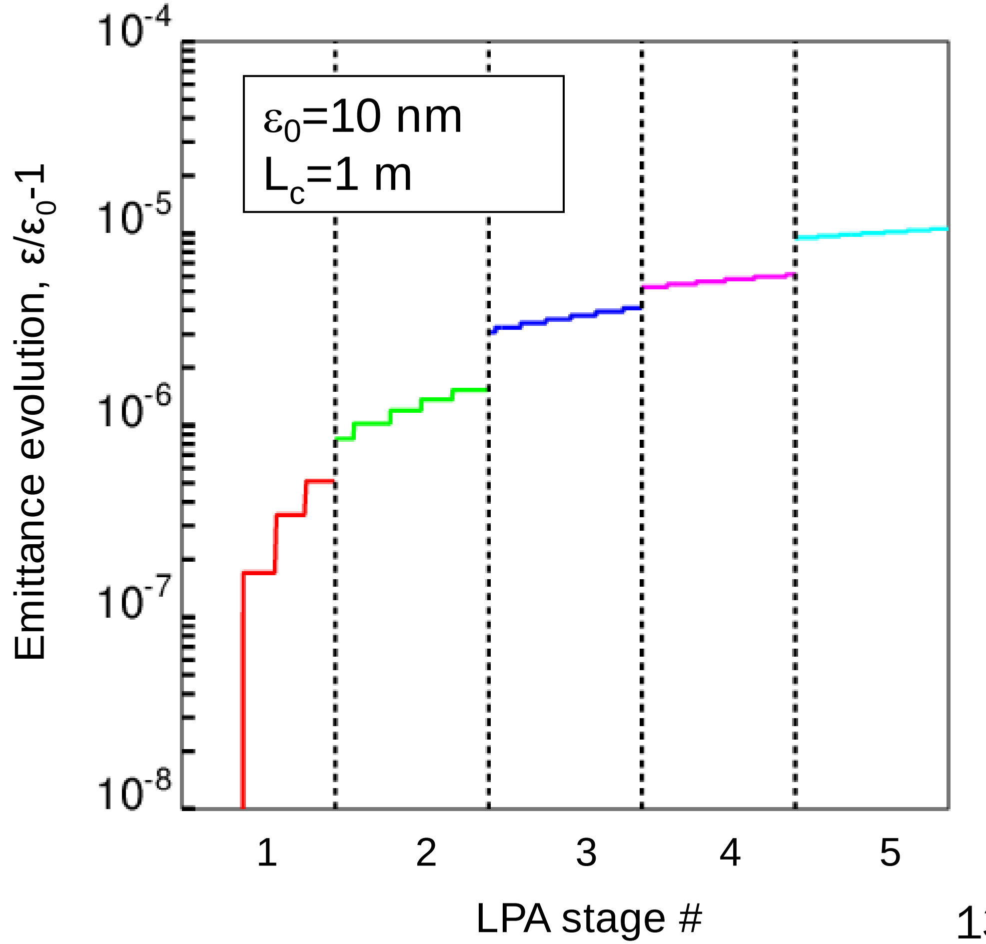


$$\Delta\varepsilon \simeq \left(\frac{\varepsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\frac{s}{\gamma_0}$$

For bunches with ε_0= 10 nm, σ_0=5 μm, and ~1% energy spread:

→ Δε <<1 nm in meter-scale drifts

→ Applies to any stage where σ_0 can be controlled



Ballistic (i.e., w/o focusing) inter-stage transport but refocusing w/ conventional quadrupoles in <~ m scale distance possible

Example of LWFA-based electron-positron collider parameters developed to guide R&D

Starting point for future studies!

Laser driver parameters

Laser pulse energy	6.5 J
Laser (FWHM) pulse duration	130 fs
Laser pulse peak power	50 TW
Laser wavelength	1 μm
Plasma density	10^{17} cm^{-3}
Plasma channel length	1.7 m
Plasma channel radius	22 μm
Peak accelerating field	6 GV/m
Beam peak current	3 kA
RMS beam length	8.5 μm
Loaded accelerating gradient	3 GV/m
Particle energy gain per stage	5 GeV

https://iopscience.iop.org/article/10.1088/1748-0221/18/09/P09022/pdf

Machine and particle beam parameters

Technology	LWFA	LWFA	LWFA
Beam Aspect Ratio	Flat	Flat	Round
Center-of-Mass Energy	1	3	15
E_{beam} (TeV)	0.5	1.5	7.5
γ	9.78E5	2.94E6	1.47E7
ε_x (mm mrad)	0.1	0.02	0.1
ε_y (mm mrad)	0.01	0.007	0.1
β^*_x (mm)	25	14	0.15
β^*_y (mm)	0.1	0.1	0.15
σ^*_x (nm)	50.55	9.77	1.01
σ^*_y (nm)	1.01	0.49	1.01
N_{bunch} ($\times 10^9$)	1.20	1.20	7.50
f (kHz)	46.8	46.8	3.44
σ_z (um)	8.4	8.4	2.2
Υ	2	37	22466
n_γ	0.8	1.5	5.7
P_{beam} (MW)	4.5	13.5	31.0
$2P_{\text{beam}}$ (MW)	9.0	27.0	61.9
$\mathcal{L}_{\text{geo}}$ ($\times 10^{34}$ cm^{-2} s^{-1})	1.05	11.3	150
$\mathcal{L}_{\text{beamstrahlung}}$ ($\times 10^{34}$ cm^{-2} s^{-1})	2.09	21.7	152
$\eta_{\text{wall-to-drive}}$	0.4	0.4	0.5
$\eta_{\text{drive-to-main}}$	0.2	0.2	0.12
η_{total}	0.08	0.08	0.06
P_{site} (MW)	113	338	1032
$\mathcal{L}_{\text{geo}}/P_{\text{site}}$ (1e34/MW)	0.01	0.03	0.05
$\mathcal{L}_{\text{GP,tot}}$ ($\times 10^{34}$ cm^{-2} s^{-1})	1.53	25.8	600
$\mathcal{L}_{\text{GP,top}}$ 1% (20%) ($\times 10^{34}$ cm^{-2} s^{-1})	1.03	8.72	50
$\mathcal{L}_{\text{GP,tot}}/P_{\text{site}}$	0.01	0.08	0.58
$\mathcal{L}_{\text{GP,top}}/P_{\text{site}}$ 1% (20%)/Power	0.01	0.03	0.05
Length of 2 Linacs (km)	0.44	1.3	6.5
Length of Facility	3.5	4.5	9.5

Recap of some LWFA linac challenges to be considered [and potential solutions (some requiring significant R&D)]

- **Laser diffraction**

-Self-guiding in nonlinear regime
-Guiding in pre-formed plasma channel

- **Laser-particle beam dephasing**

-Plasma tapering

- **Laser depletion w/ high gradient**

-Staging with compact driver in-coupling

- **Positron acceleration**

-Use plasma columns/filaments
-Use hollow channels

- **High laser-to-beam efficiency (w/ no energy spread growth)**

-Shaped particle beams
-Laser energy recovery

- **Heating of plasma**

-Use an "energy recovery" pulse

- **High-average laser power**

-Fiber laser combining

- **Scattering in plasma**

-Strong plasma focusing
-Use (near-)hollow channels

- **Emittance growth via ion motion**

-Use (near-)hollow channel
-Adiabatic, slice-by-slice, matching

- **Emittance mixing due to resonances**

-Use hollow channel and round particle beams

- **Beamstrahlung mitigation**

-Short bunches

- **Transverse beam instabilities**

-Detune betatron freq. (e.g., ion motion or energy spread)
-Stagger tuning

- **Alignment tolerances:**

-Control beam size

- **Preserving beam quality in plasma mirror**

-Use thin plasma mirror w/ hole

- **Control plasma channel properties**

-Use OFI-like techniques

- **Quality-preserving staging**

-Use achromatic transport for beams
-Use hollow channels

- **Increase efficiency**

-Use energy recovery

- **Beam polarization**

- **Interaction between beam and deflected laser**

-Use properly shaped plasma mirror
-Acceleration in later plasma periods

- **…..**

Example of tasks for LWFA linac

1. Define acceptable electron/positron beam parameters (requires interaction with other WGs);
2. Design LWFA stage able to deliver such beams (assess stability, efficiency, gradient, driver properties);
3. Refine LWFA linac metrics;
4. Perform (converged) quality-preserving staging simulations (a few stages) in the low-energy section of the linac (assess stability);
5. Perform (converged) quality-preserving staging simulations (a few stages) in the high-energy section of the linac (address space-efficient staging);
6. Study laser-beam in-coupling and extraction. Does this perturb electron/positron bunches?
7. Study effect of ramps at the entrance/exit of LWFA stages (effect on the laser driver, effect on electron and positron bunches);
8. Setup modeling tools (e.g., gas dynamics, hydro, MHD, etc.) for plasma formation simulations;
9. Optimize laser guiding for realistic laser mode (w/ laser driver WG);
10. Optimize beamloading for realistic beam current profiles (w/ sources WG);
11. Assess timing tolerances and misalignments;
12. Explore energy recovery (from spent driver, from plasma)
13. …

Suggestions for other tasks are welcome!
Let us know the topic you/your group would like to contribute to!

Contribution to the ESPP report

The ESPP document will focus on a description of the Design Study, along with challenges and opportunities for a 10 TeV Wakefield Collider.

- NO “results” will be included in the document;
- List of challenges on the path to 10 TeV collisions;
- List of metrics for measuring collider goals;
- List of technologies and/or techniques to address the challenges;
- Working Group deliverables.

Deadline today (C+F took care of this)!

Discussion

- How often do we meet? (monthly?)
- How do we interface with other WGs (e.g., laser driver, simulation, BDS)
  - Do we need dedicated computing time?
- How do we document progress?
  - Example: https://indico.slac.stanford.edu/category/138/
- ....