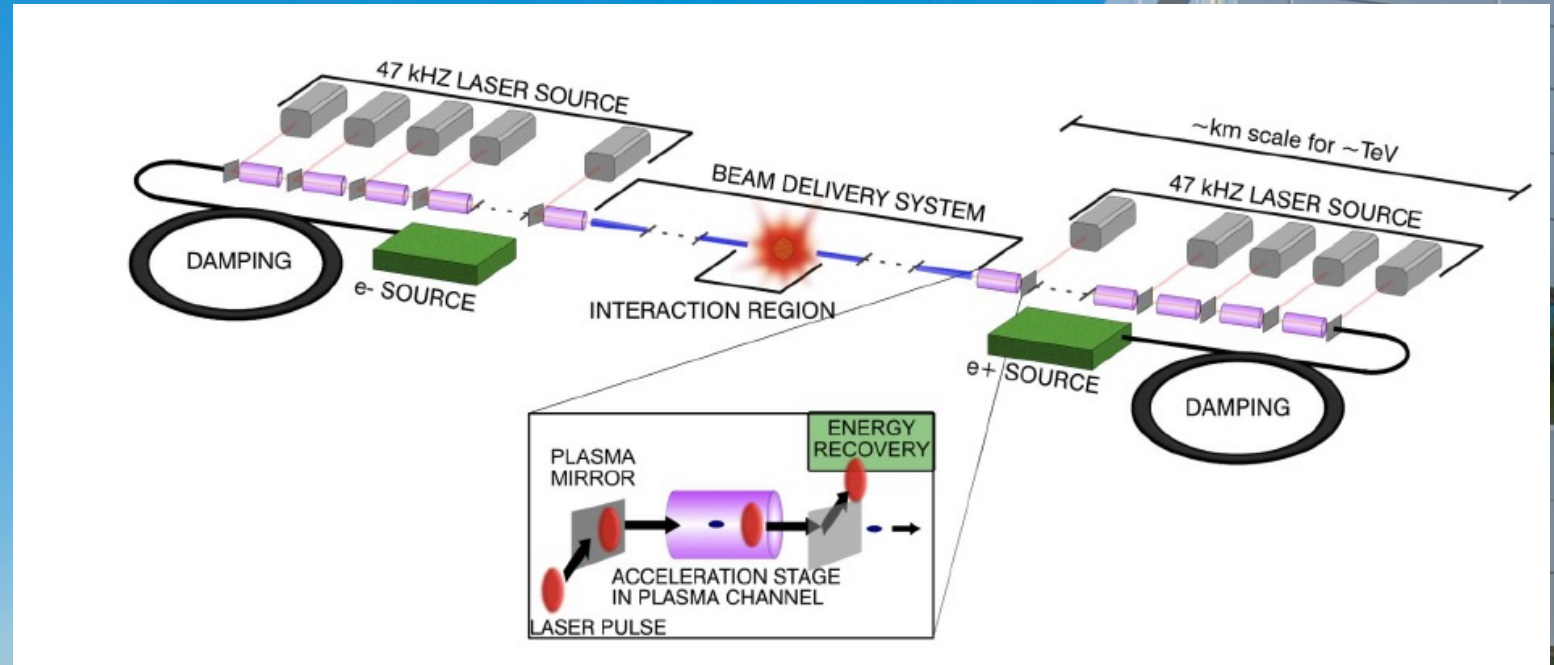


10 TeV Wakefield Collider Design Study

~~~ Joint meeting: LWFA linac + Sources ~~~

April 8, 2025

- 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
- Joint meeting**



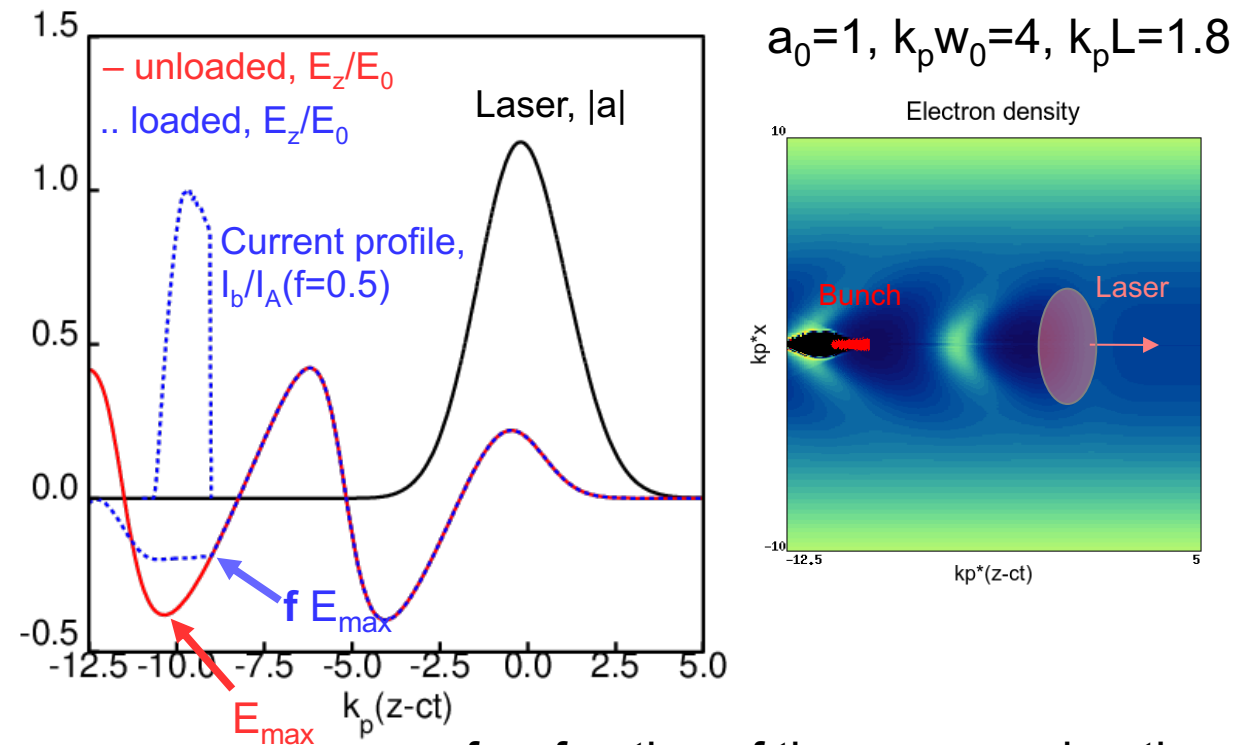
Topics for today:

1. Present parameters of particle beams required for a 10 TeV LWFA collider.
2. Can these beams be generated and how?

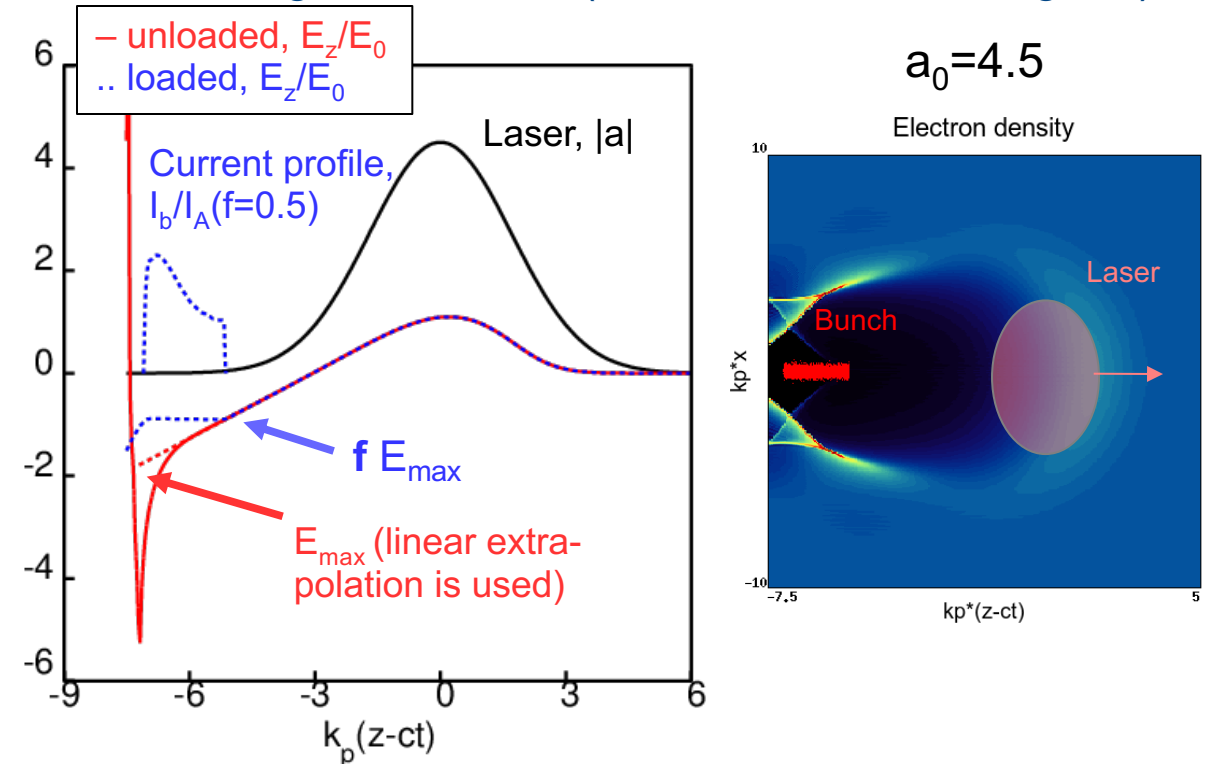
Optimal LWFA performance for collider applications requires beams with longitudinally tapered current profiles

High efficiency $\rightarrow$ bunch absorbs wake energy $\rightarrow$ bunch current profile “flattens” wakefield within bunch

Channel-guided LWFA (quasi-linear regime)



Self-guided LWFA (nonlinear / bubble regime)



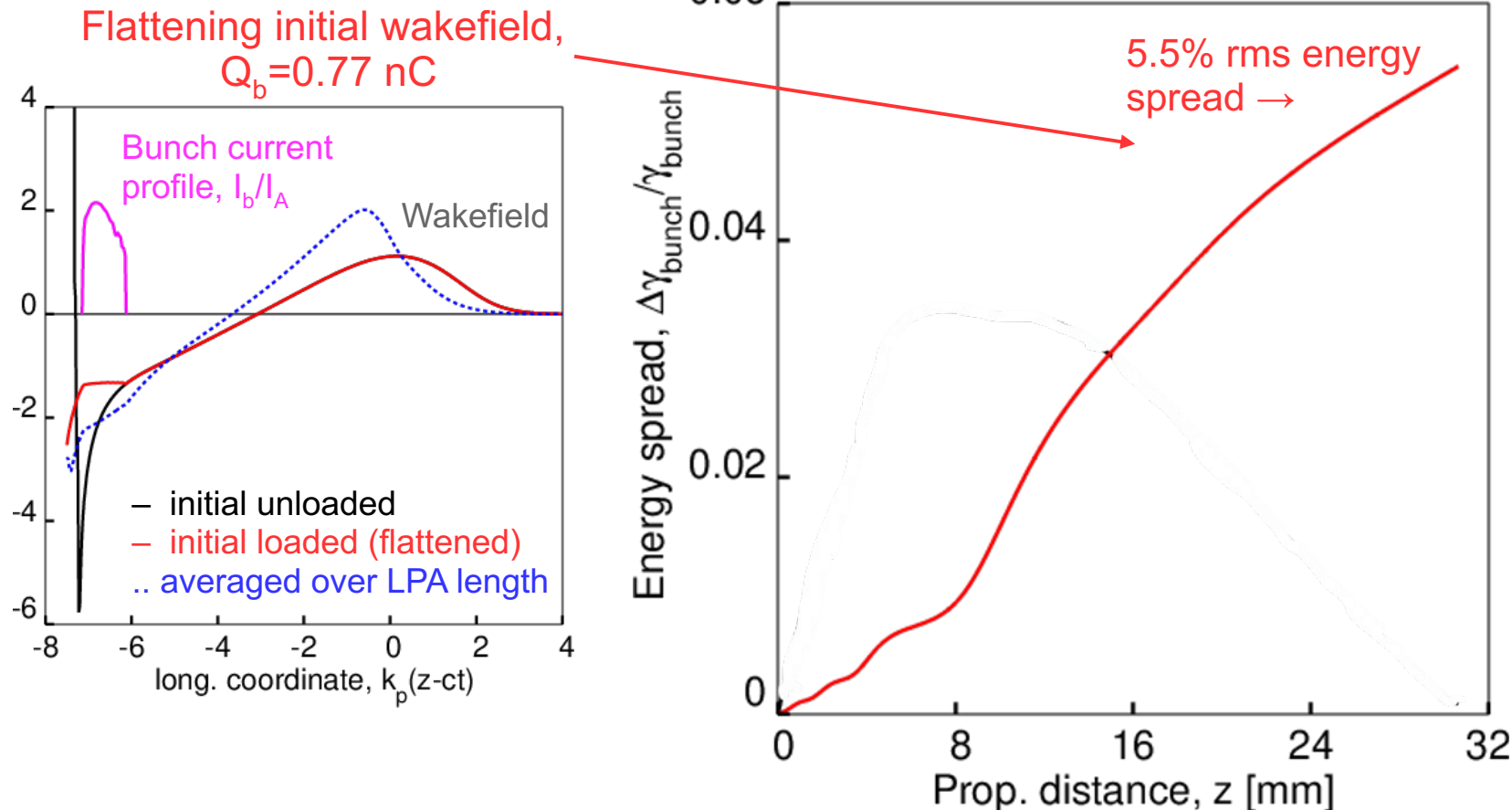
$f \rightarrow$ fraction of the max accelerating field (E_{max}) experienced by the bunch

- Linear regime (i.e., $E_z/E_0 \ll 1$) $\rightarrow$ triangular profile (Katsouleas et al., Part. Accel., 1987)
- Blowout regime (requires $\delta n \sim n_0$, i.e., $a_0 > 8-10$) $\rightarrow$ trapezoidal profile (Tzoufras PRL 2009; Dalichaouch POP 2021)

$\rightarrow$ Characteristic current profile depends on LWFA regime (can be computed numerically)

Production of beams with a small energy spread requires flattening the wakefield **AVERAGED** over the LPA length

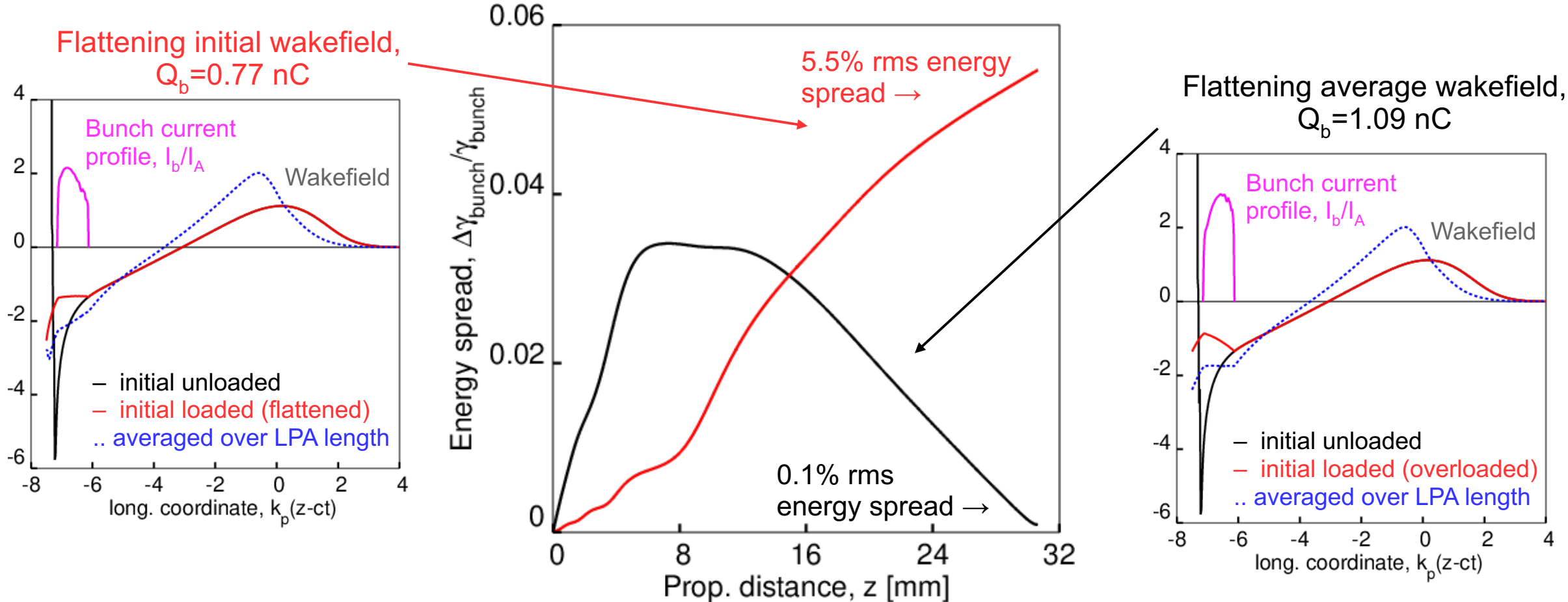
Self-guided LPA (bubble/nonlinear): $U=50$ J [$a_0=4.5$, $\lambda_0=0.8$ μm], $f=0.75$



- Current profile that flattens initial wake not optimal to minimize energy spread
→ bunch acquires energy chirp (= energy spread) because of laser evolution and beam-driver slippage

Production of beams with a small energy spread requires flattening the wakefield AVERAGED over the LPA length

Self-guided LPA (bubble/nonlinear): $U=50$ J [$a_0=4.5$, $\lambda_0=0.8$ μm], $f=0.75$



- Current profile that flattens initial wake not optimal to minimize energy spread
 - bunch acquires energy chirp (= energy spread) because of laser evolution and beam-driver slippage
- Optimal beam profile: energy chirp imparted initially (overloading) compensated during acceleration
 - minimum energy spread achieved at the end of the stage

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

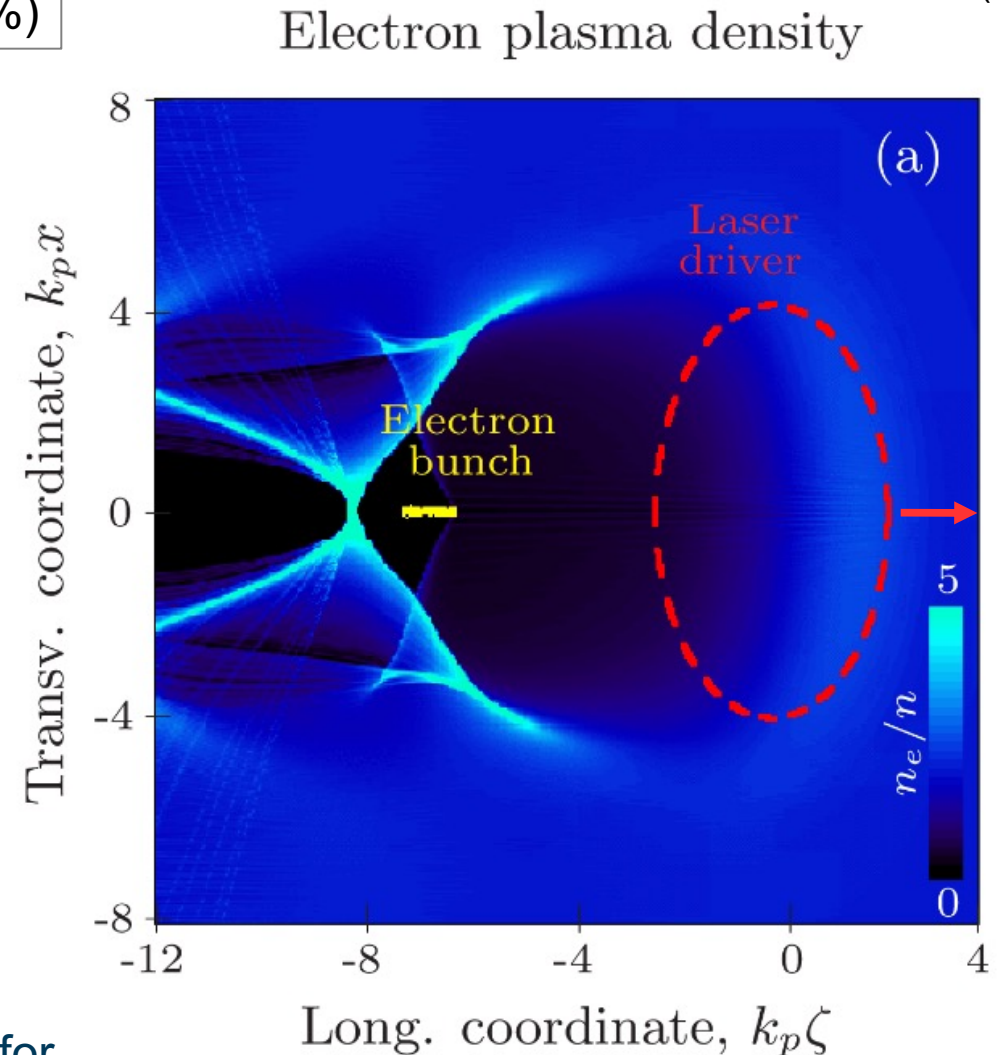
Schroeder et al.,
JINST (2022)

Laser: $U=50$ J, $\lambda_0=1.0$ μm , $a_0=4.5$, $T_0=80$ fs, $w_0=36$ μm
Plasma: $n_0=3.4\times 10^{17}$ cm^{-3} , stage length = 3.1 cm, linear taper (+74%)

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

Energy considerations:

- Wake-to-bunch energy transfer = 40%
 - Laser driver depletion = 20% $\rightarrow$ remaining laser driver energy could be returned to the grid with photovoltaic
- $\rightarrow$ ~320 LPA stages/TeV
- $\rightarrow$ Stable (w/ ion motion) + no emittance growth from Coulomb scattering + negligible synchrotron radiation-induced energy spread
- $\rightarrow$ Not suitable for positrons
- $\rightarrow$ Strong focusing yields small bunch size ($\sim$ nm @ $\sim$ TeV energies for collider-relevant emittances): **challenging for inter-stage transport and alignment!**



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

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	$4.6 \times 10^{17} \text{ cm}^{-3}$
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	$2 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
Facility site power (2 linacs)	415 MW

In addition to high charge (w/ current tapering) normalized emittances on the order of 10-100 nm are needed

If background ion motion is present emittance preservation requires slice-dependent transverse beam phase-space tailoring/1

Low emittance + high charge + high energy:

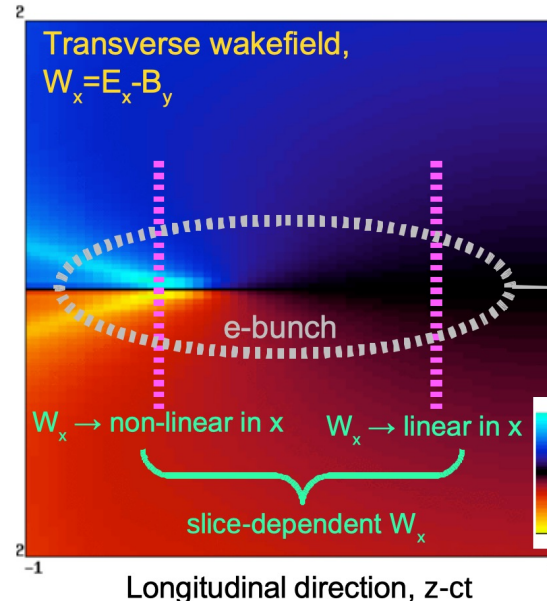
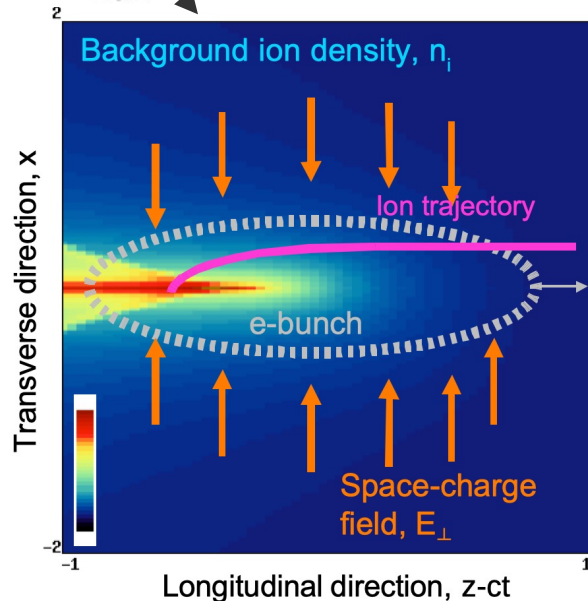
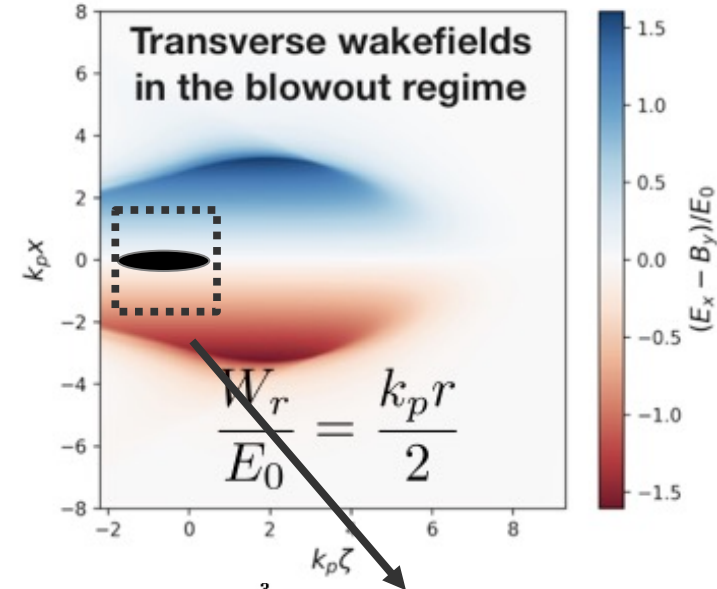
→ small matched beam size and high beam density

→ large beam space charge fields

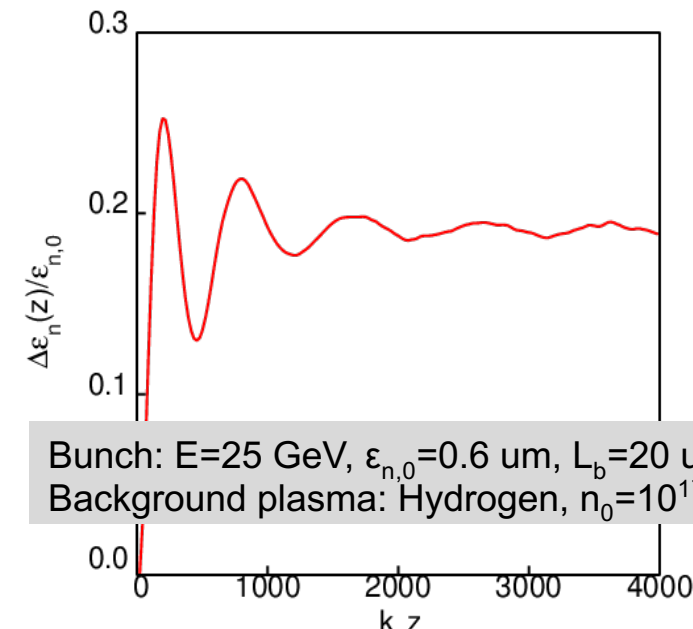
→ **background ion motion**

$$\sigma_x^2 = \frac{\epsilon_n}{\gamma k_\beta} = \sqrt{\frac{2}{\gamma}} \frac{\epsilon_n}{k_\beta}$$

Rosenzweig et al., PRL (2005)
An et al., PRL (2017)
Benedetti et al., PRAB (2017)



Projected emittance evolution



Bunch quality degradation:
→ **emittance growth**

Bunch: $E=25$ GeV, $\epsilon_{n,0}=0.6$ μm , $L_b=20$ μm , $Q_b=1.6$ nC
Background plasma: Hydrogen, $n_0=10^{17}$ cm^{-3}

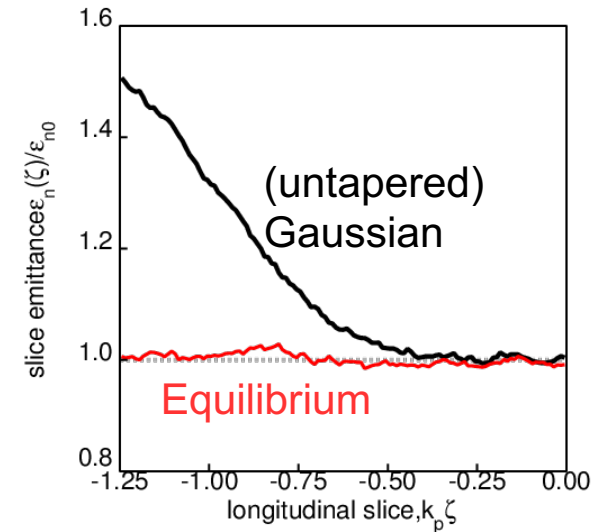
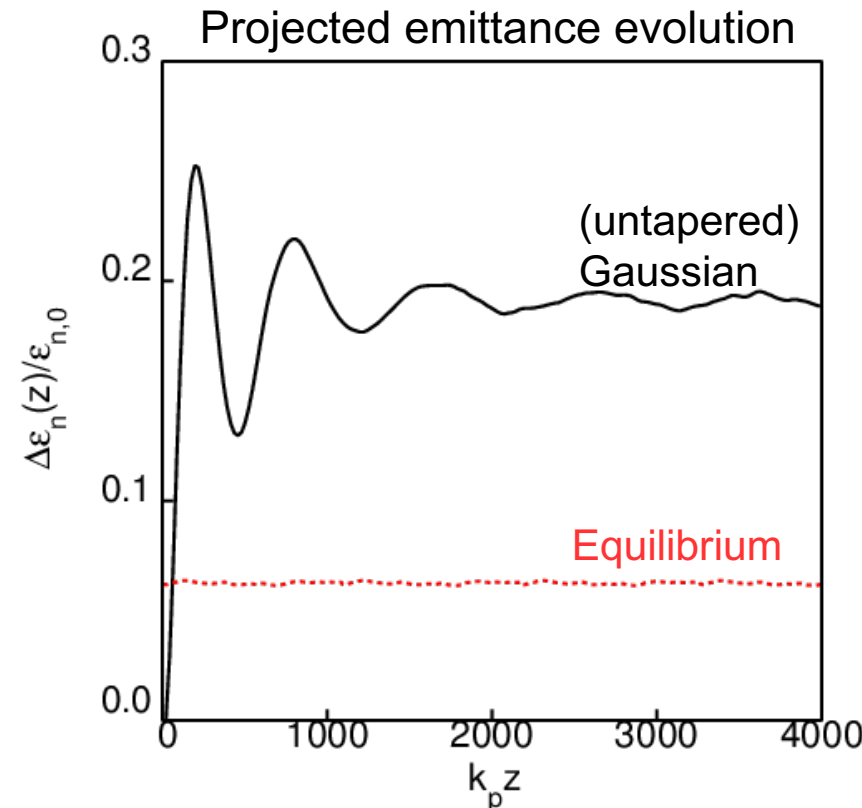
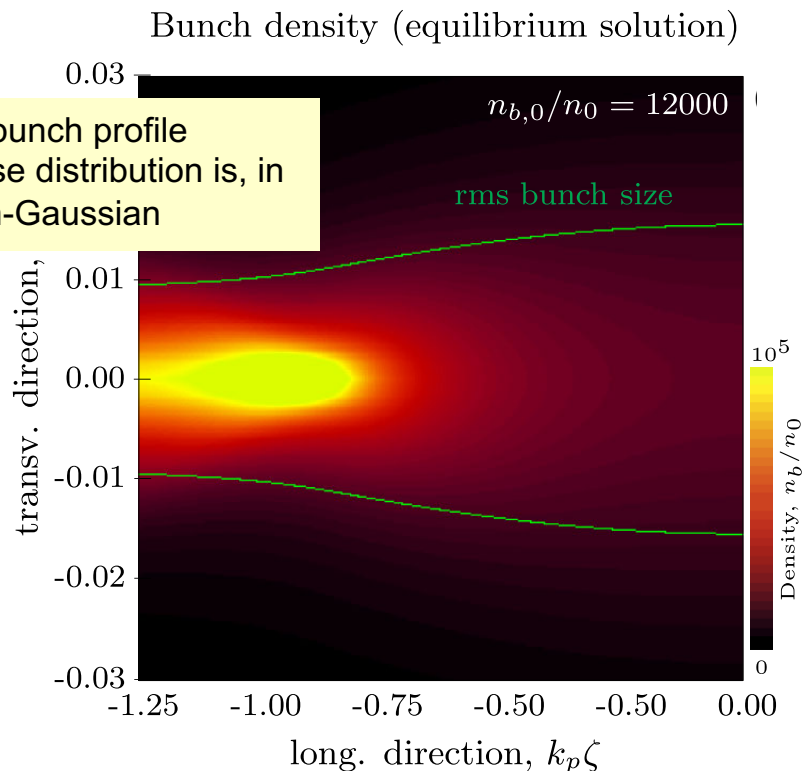
If background ion motion is present emittance preservation might require slice-dependent transverse beam phase-space tailoring/2

Slice-by-slice matching of the bunch in presence of ion motion requires longitudinally tailoring the bunch transverse phase-space distribution:

- slice emittance is kept constant;
- arbitrary longitudinal current profile possible;

Bunch: $E=25$ GeV, $\varepsilon_{n,0}=0.6$ μm , $L_b=20$ μm , $Q_b=1.6$ nC

Background plasma: Hydrogen, $n_0=10^{17}$ cm^{-3}



← No emittance growth!
[for matched solution slice
emittance $\neq$ projected
emittance]

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

Schroeder et al.,
NIMA (2016)

Laser: $U=8.9$ J, $\lambda_0=1.0$ μm , $a_0=1.8$, $T_0=73$ fs, $w_0=41$ μm

Plasma (hollow channel): $n_0=0.96 \times 10^{17}$ cm^{-3} , $R_c=24$ μm , stage length = 78 cm w/ optimal taper

$\Delta W_{\text{bunch}} = 5.05$ GeV (6.5 GV/m)

$Q_{\text{bunch}} = 0.24$ nC – $L_{\text{bunch}}=30$ μm – $I_{\text{bunch}}=5$ kA

Energy spread = 0.8% (with shaped bunch current)

Energy considerations:

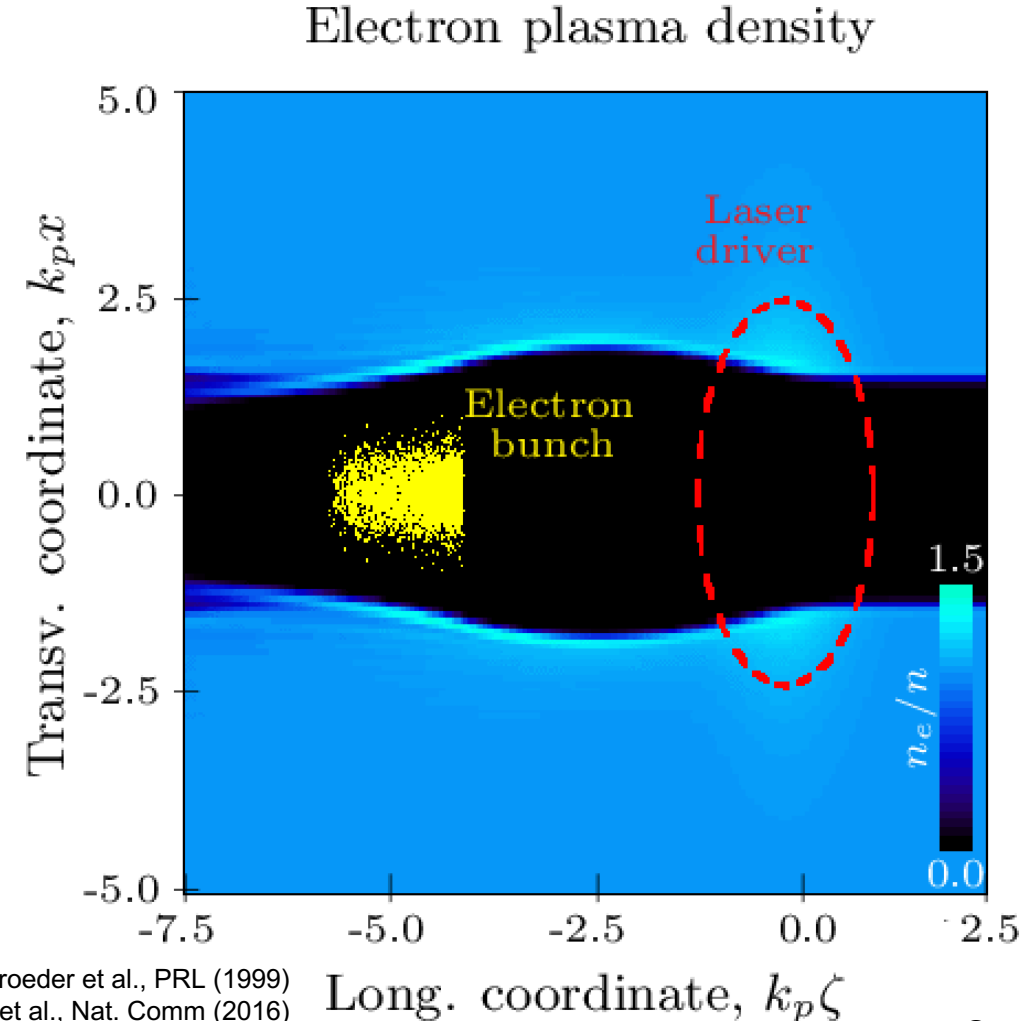
- Wake-to-bunch energy transfer = 68%
- Laser driver depletion = 20% $\rightarrow$ remaining laser driver energy could be returned to the grid with photovoltaic

$\rightarrow$ ~200 LPA stages/TeV

$\rightarrow$ Negligible emittance growth from Coulomb scattering + no energy spread from synchrotron radiation + suitable for positrons

$\rightarrow$ Unstable w/o strong focusing: potential stabilization mechanisms are currently being investigated

$\rightarrow$ Hollow-channel allows for large ($\sim \mu\text{m}$ -scale) beam size:
relaxed constraints on inter-stage transport and alignment!

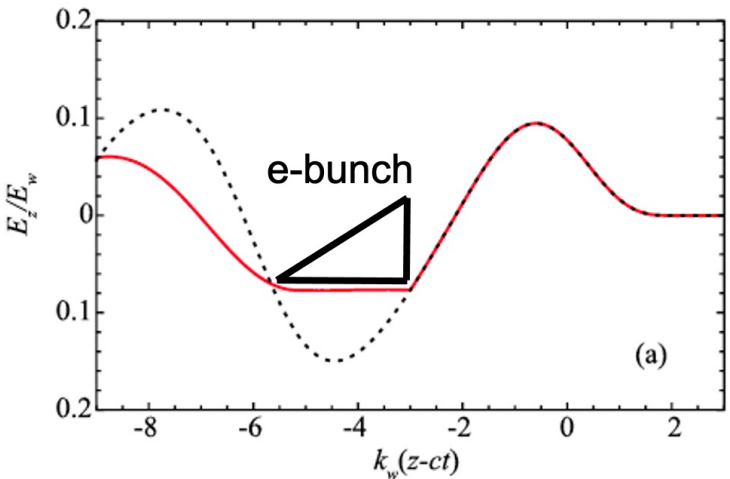


Schroeder et al., PRL (1999)
Gessner et al., Nat. Comm (2016)
Lindstrøm et al., PRL (2018)

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

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



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
$N_{\text{bunch}} (\times 10^9)$	1.20	1.20	7.50
f (kHz)	46.8	46.8	3.44
σ_z (μm)	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
$\mathcal{L}_{\text{geo}} (\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1})$	1.05	11.3	150
$\mathcal{L}_{\text{beamstrahlung}} (\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1})$	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
$\mathcal{L}_{\text{GP,tot}} (\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1})$	1.53	25.8	600
$\mathcal{L}_{\text{GP,top 1\% (20\%)}} (\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1})$	1.03	8.72	50
$\mathcal{L}_{\text{GP,tot}}/P_{\text{site}}$	0.01	0.08	0.58
$\mathcal{L}_{\text{GP,top 1\% (20\%)}}/P_{\text{site}}$	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

Discussion points

Summary of electron (and positron) beam parameters of collider applications:

- $Q_b \sim 100 \text{ pC} - 1 \text{ nC}$ w/ optimally tailored current profile
- $L_b \sim 10 \text{ um}$
- $\varepsilon_b \sim 0.1 \text{ um}$

- Should we consider plasma-based injectors on the electron arm of the collider (e.g., Dalichaouch et al., <https://arxiv.org/pdf/2406.04585>, optimized two-color laser ionization injection, optimized density gradient injection, etc.)
- Can positron beams be generated with the required emittances and tailored current profiles? (N.B.: we currently do not have a viable scheme for a positron linac)
-