



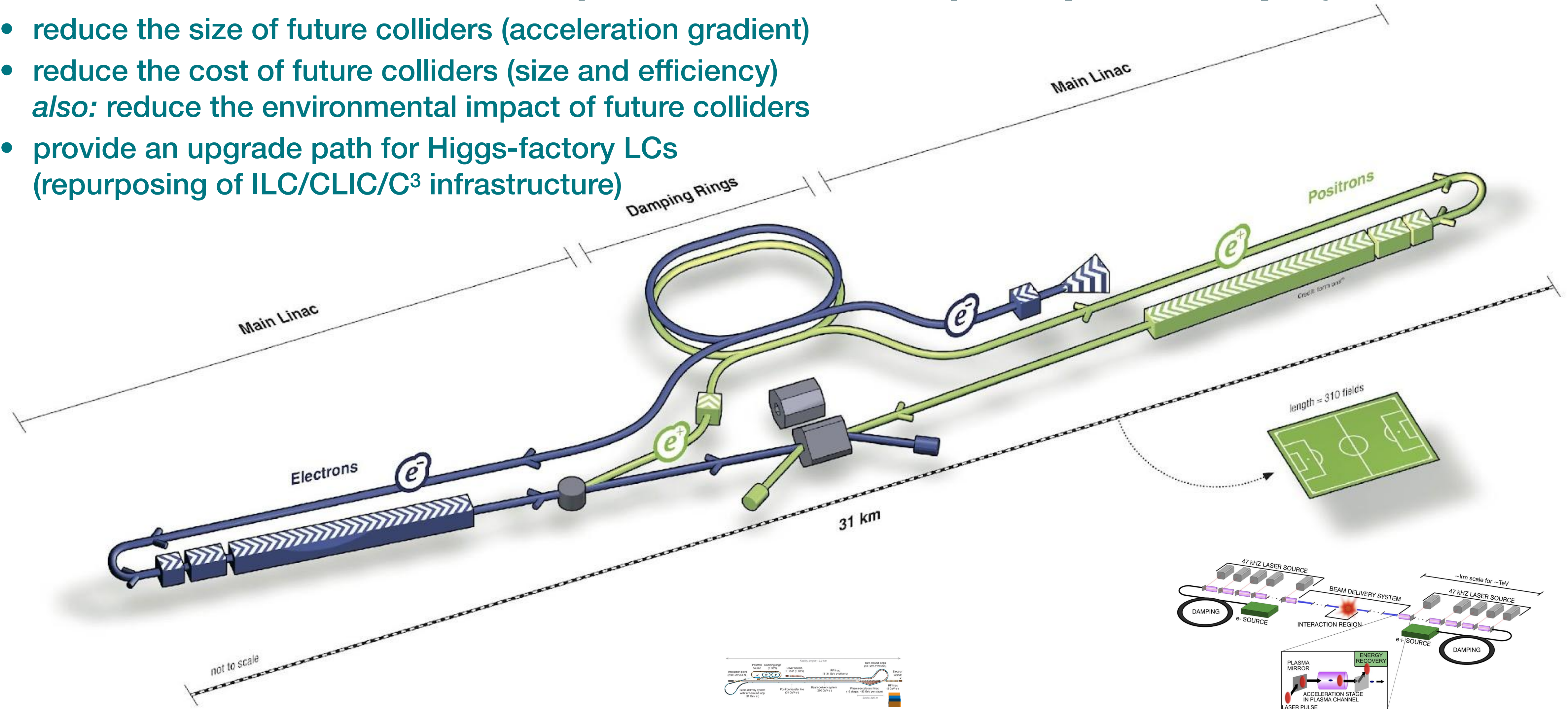
10 TeV Wakefield Collider Design Study

Introduction

Laser Working Group - Kickoff Meeting
January 24, 2025

Wakefield accelerators ($\gtrsim 1$ GV/m fields) for particle physics

- reduce the size of future colliders (acceleration gradient)
- reduce the cost of future colliders (size and efficiency)
also: reduce the environmental impact of future colliders
- provide an upgrade path for Higgs-factory LCs (repurposing of ILC/CLIC/C³ infrastructure)



ILC / 500 GeV / 31 km



HALHF / 250 GeV / 3.3 km

Foster, D'Arcy, and Lindstrøm, *NJP* 25, 093037 (2023)

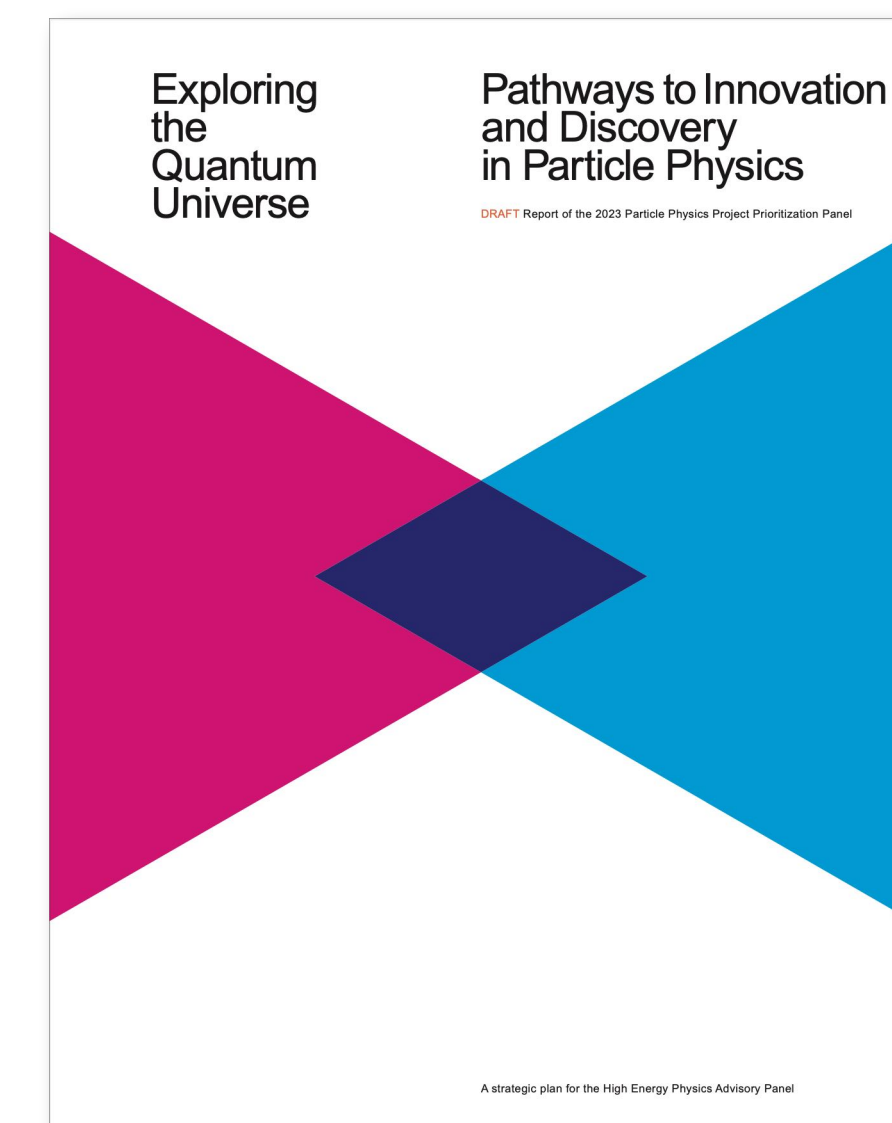
Wakefield Collider / 15 TeV / 6.6 km*

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

*for the linac, not including the BDS

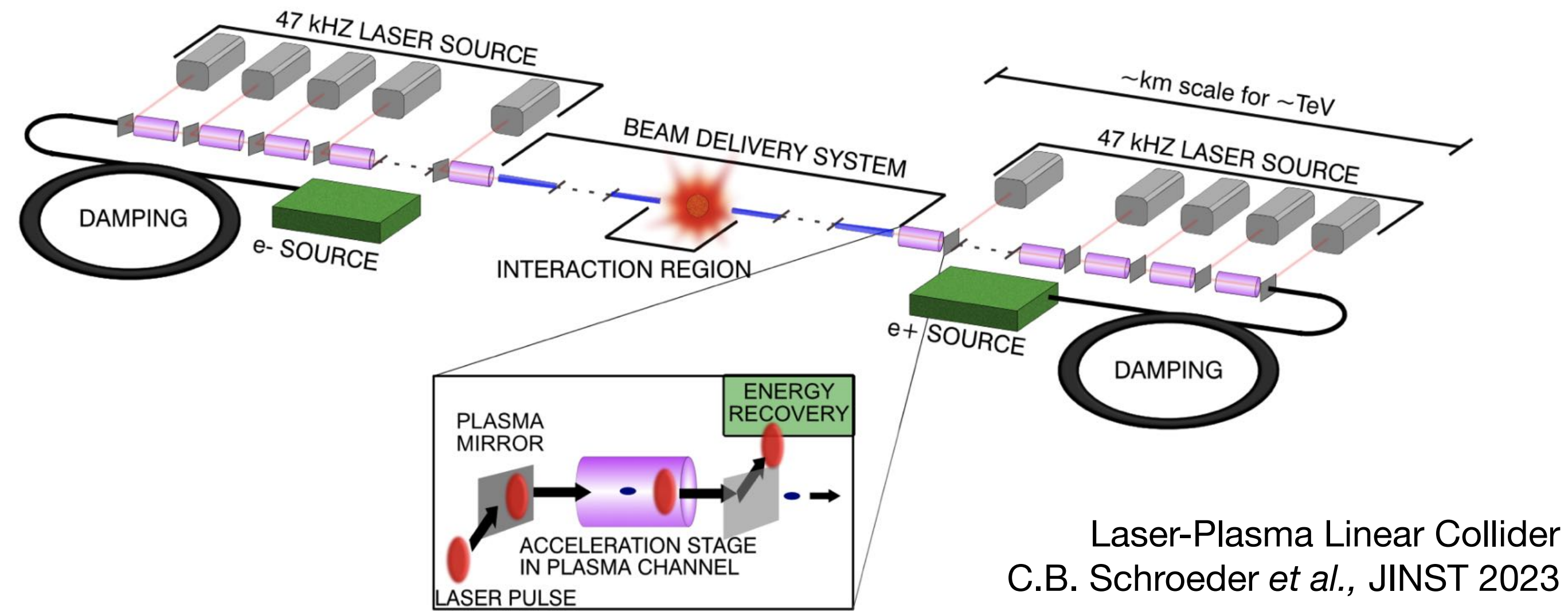
Welcome to the Design Study

- We want to uncover a path to the **energy frontier (10 TeV)** in a Linear Collider Facility.
- Just as FCC-hh builds on FCC-ee infrastructure, we envision a 10 TeV Linear Collider could build on a Linear Collider Higgs Factory.
- The goals for the **10 TeV pCM Wakefield Accelerator Collider Design Study** have been set by the 2023 P5 Report:
 - “. . . delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout.”
- Plan to complete the design report by 2028 with many updates and inputs (including ESPP) along the way.



What is an end-to-end design concept?

It describe the system with sub-systems and how these fit together and can be self-consistently integrated



Challenges

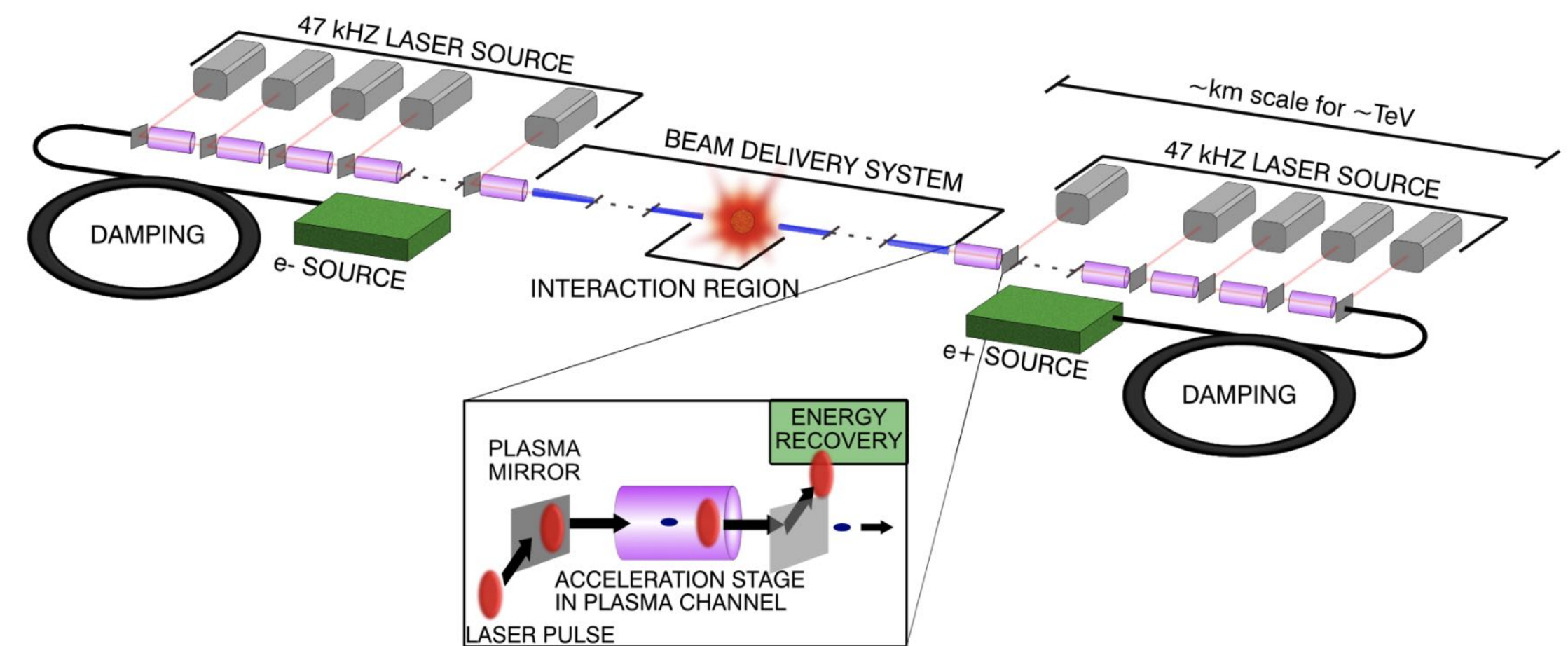
- Stability
- Energy recovery
- Repetition rate
- Efficiency
- Geometric gradient
- Positron acceleration
- Stage coupling
- Beam delivery system
- Jitter budget

High-level concept to guide ongoing technology development



Working Groups

- 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



Green = Broader accelerator community

Orange/blue/purple = AAC specific

Red = HEP and broader community



Starting machine parameters (they will evolve)

Technology	PWFA	PWFA	PWFA	PWFA	SWFA	SWFA	SWFA	LWFA	LWFA	LWFA
Beam Aspect Ratio	Flat	Flat	Flat	Round	Flat	Flat	Round	Flat	Flat	Round
Center-of-Mass Energy	1	3	15	15	1	3	15	1	3	15
E_{beam} (TeV)	0.5	1.5	7.5	7.5	0.5	1.5	7.5	0.5	1.5	7.5
γ	9.78E5	2.94E6	1.47E7	1.47E7	9.78E5	2.94E6	1.47E7	9.78E5	2.94E6	1.47E7
ϵ_x (mm mrad)	0.66	0.66	0.66	0.1	0.66	0.66	0.1	0.1	0.02	0.1
ϵ_y (mm mrad)	0.02	0.02	0.02	0.1	0.02	0.02	0.1	0.01	0.007	0.1
β_x^* (mm)	5	5	5	0.15	5	5	0.15	25	14	0.15
β_y^* (mm)	0.1	0.1	0.1	0.15	0.1	0.1	0.15	0.1	0.1	0.15
σ_x^* (nm)	58.07	33.53	15	1.01	58.07	33.53	1.01	50.55	9.77	1.01
σ_y^* (nm)	1.43	0.83	0.4	1.01	1.43	0.83	1.01	1.01	0.49	1.01
$N_{\text{bunch}} (\times 10^9)$	5	5	5	5	3.13	3.13	3.13	1.20	1.20	7.50
f (kHz)	4.2	14	13.12	7.73	11	36	19.8	46.8	46.8	3.44
σ_z (um)	5	5	5	5	40	40	40	8.4	8.4	2.2
Υ	15	78	867	6590	1	6	515	2	37	22466
n_γ	1.5	1.5	1.5	5.7	2.2	2.2	8.4	0.8	1.5	5.7
P_{beam} (MW)	1.7	16.8	78.8	55.0	2.8	27.0	74.4	4.5	13.5	31.0
$2P_{\text{beam}}$ (MW)	3.4	33.6	157.6	110.0	5.5	54.1	148.7	9.0	27.0	61.9
$\mathcal{L}_{\text{geo}} (\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1})$	1.01	10.1	47.1	150	1.03	10.1	151	1.05	11.3	150
$\mathcal{L}_{\text{beamstrahlung}} (\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1})$	1.99	19.9	99.4	152	2.03	20	152	2.09	21.7	152
$\eta_{\text{wall-to-drive}}$	0.4	0.4	0.4	0.4	0.774	0.774	0.774	0.4	0.4	0.5
$\eta_{\text{drive-to-main}}$	0.375	0.375	0.375	0.375	0.42	0.42	0.42	0.2	0.2	0.12
η_{total}	0.15	0.15	0.15	0.15	0.325	0.325	0.325	0.08	0.08	0.06
P_{site} (MW)	22	224	1051	619	17	166	457	113	338	1032
$\mathcal{L}_{\text{geo}}/P_{\text{site}} (1e34/\text{MW})$	0.04	0.04	0.04	0.08	0.06	0.06	0.11	0.01	0.03	0.05
$\mathcal{L}_{\text{GP,tot}} (\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1})$	1.83	18.5	87.6	1570	2.08	21.3	420	1.53	25.8	600
$\mathcal{L}_{\text{GP,top 1\% (20\%)}} (\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1})$	0.69	6.23	50	50	0.85	6.14	50	1.03	8.72	50
$\mathcal{L}_{\text{GP,tot}}/P_{\text{site}}$	0.08	0.08	0.08	2.54	0.12	0.13	0.92	0.01	0.08	0.58
$\mathcal{L}_{\text{GP,top 1\% (20\%)}}/P_{\text{site}}$	0.03	0.03	0.05	0.08	0.05	0.04	0.11	0.01	0.03	0.05
Length of 2 Linacs (km)	1	3	14	14	5	15	75	0.44	1.3	6.5
Length of Facility	14	14	14	14	8	18	90	3.5	4.5	9.5

Table 1. Parameters of the advanced Plasma Wakefield (PWFA), Structure-based Wakefield (SWFA), and Laser Wakefield (LWFA) colliders. Υ is the beamstrahlung parameter. $\mathcal{L}_{\text{GP,tot}}$ and $\mathcal{L}_{\text{GP,top}}$ refer to the total and top percentage luminosity derived from GUINEA-PIG simulations. At 1 and 3 TeV CM, the top percentage luminosity is within 1% of the CM energy. At 15 TeV CM, the top percentage luminosity is within 20% of the CM energy. The simulations shown in figure 2 are represented by the data in the ‘PWFA Flat, 15 TeV’ and ‘PWFA Round, 15 TeV’ columns.

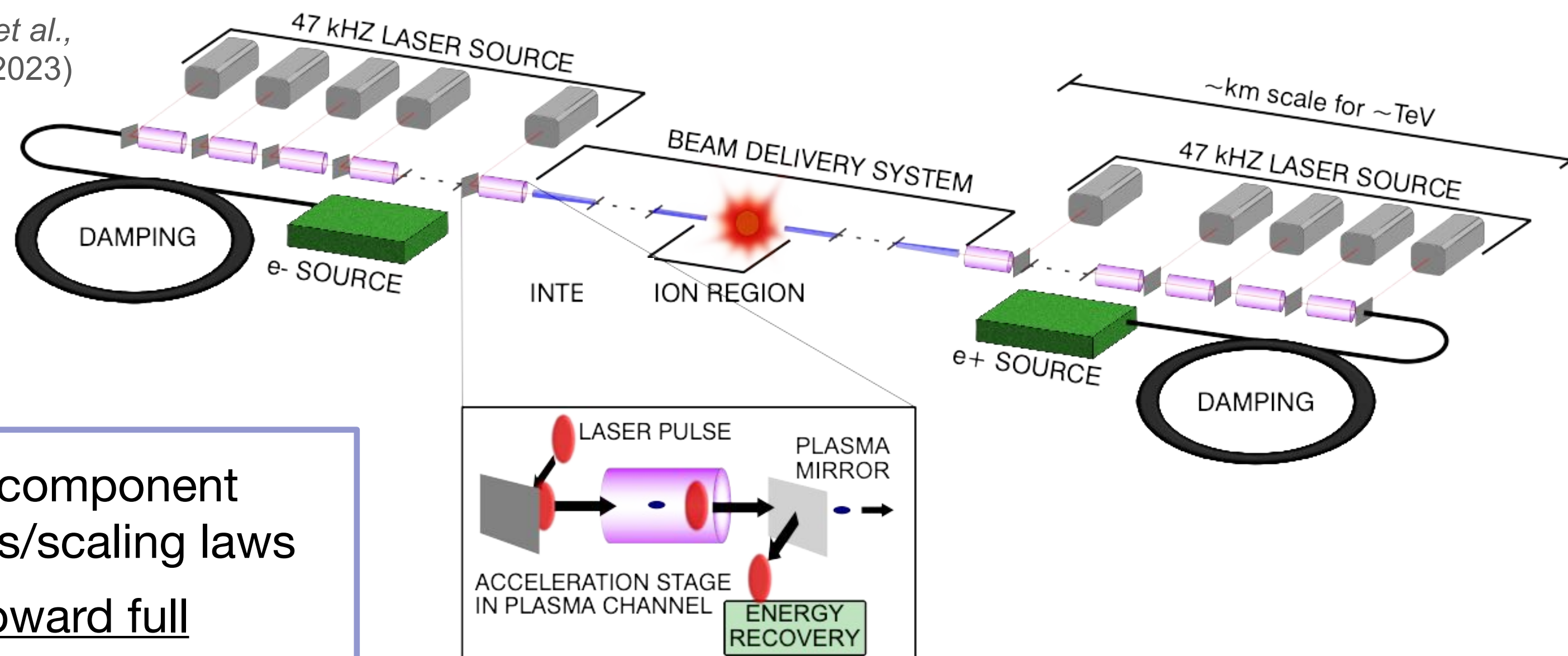


Conceptual physics considerations determine parameter ranges

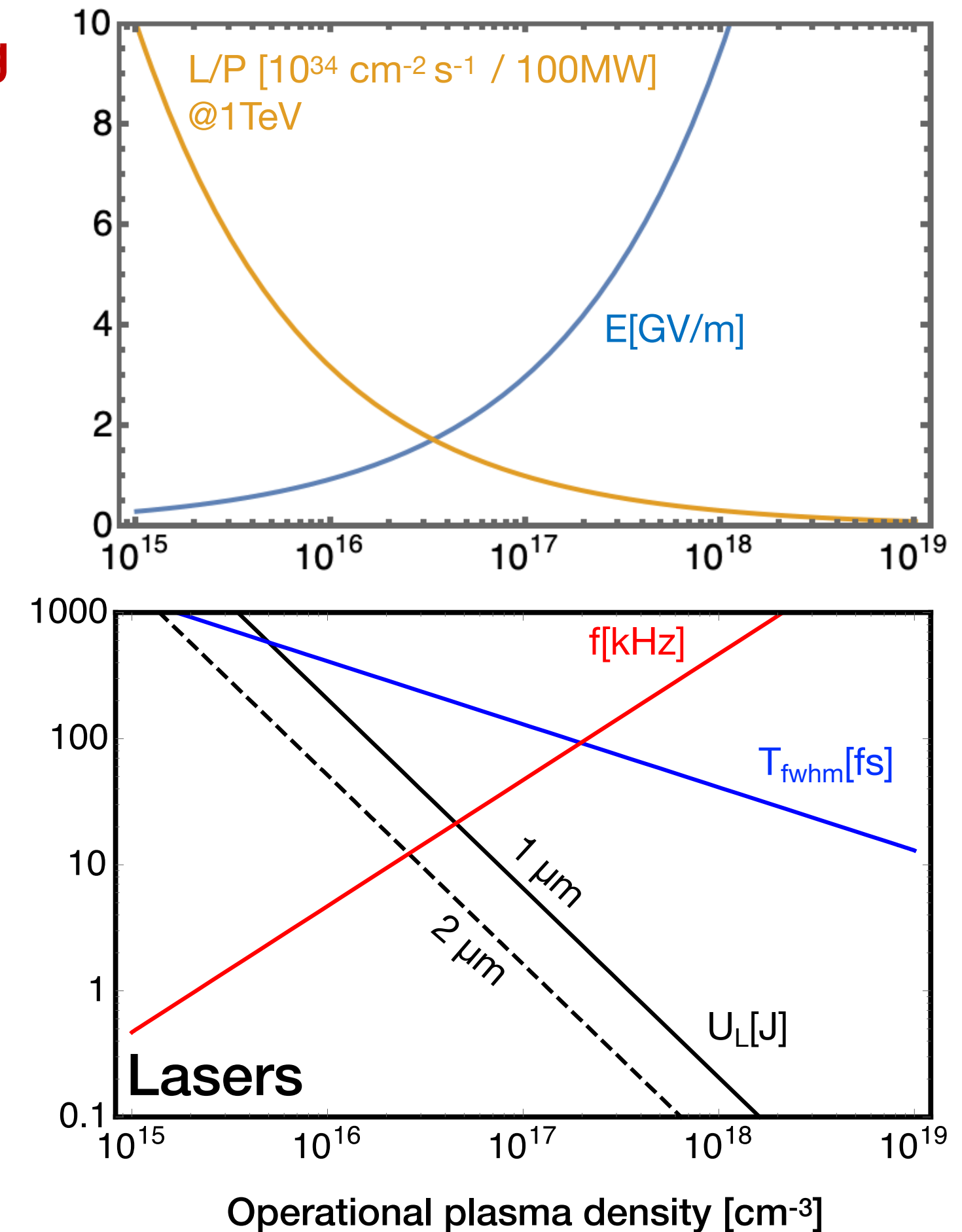
Basic design choices driven by system optimization

- Minimizing linac length (gradient $> \text{GV/m}$)
 - Maximizing **energy efficiency** (luminosity/power)
 - Plasma density sets bunch charge (also limited by Beamstrahlung), luminosity requires **repetition rate**
- } Restricts **plasma density** range, energy gain per stage \rightarrow **staging**

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



- Based on component simulations/scaling laws
- Working toward full self-consistency



Conceptual collider parameter sets derived during Snowmass

T. Barklow *et al.*, JINST 18 P09022 (2023);
C.B. Schroeder *et al.*, JINST 18 T06001 (2023)



Capability gap in laser driver technology exists

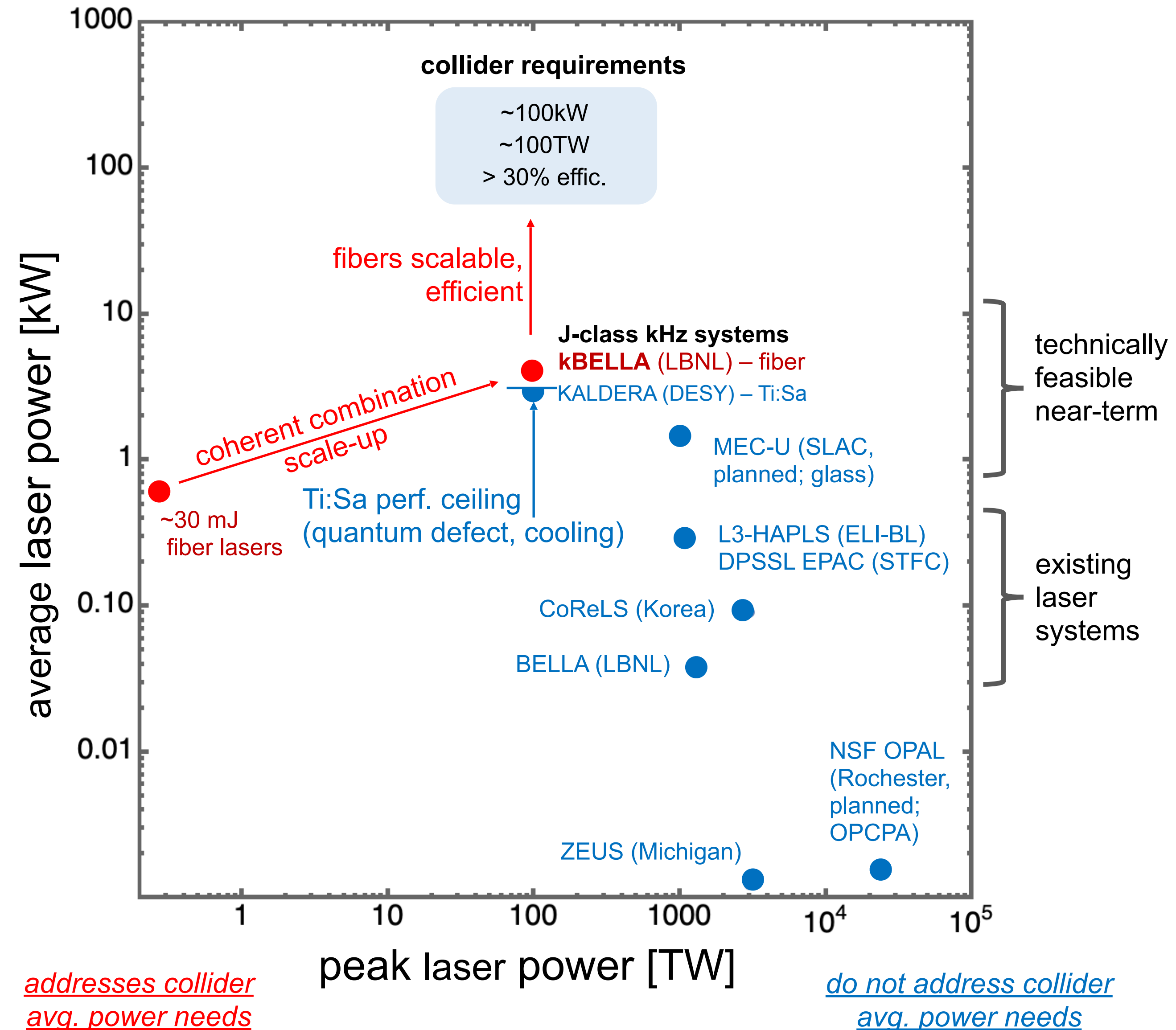
Novel laser technology needed to fulfill collider demands

in repetition rate (Hz → ~10s kHz), efficiency (0.1% → 10s %)

Promising emerging laser architectures

- Cryo-cooled **Yb:YAG** ($\lambda = 1 \mu\text{m}$), R&D at CSU
- **Tm:YLF** ($\lambda = 1.9 \mu\text{m}$), R&D at LLNL
- **Coherent combination of fiber lasers** ($\lambda = 1 \mu\text{m}$), R&D at Michigan, LBNL, Jena, École Polytechnique

Example: kBELLA addresses the driver rate and efficiency gap



Conclusion

The P5 Report and particle physics community call on us to deliver an end-to-end design study of a 10 TeV pCM collider based on WFA technology.

Laser wakefield accelerators rely on advancing the state of the art in laser technology.

- 1) We need to understand the “menu of options” for collider laser technology.
- 2) We need to apply collider-relevant metrics to the different technologies and develop the most promising paths forward.

