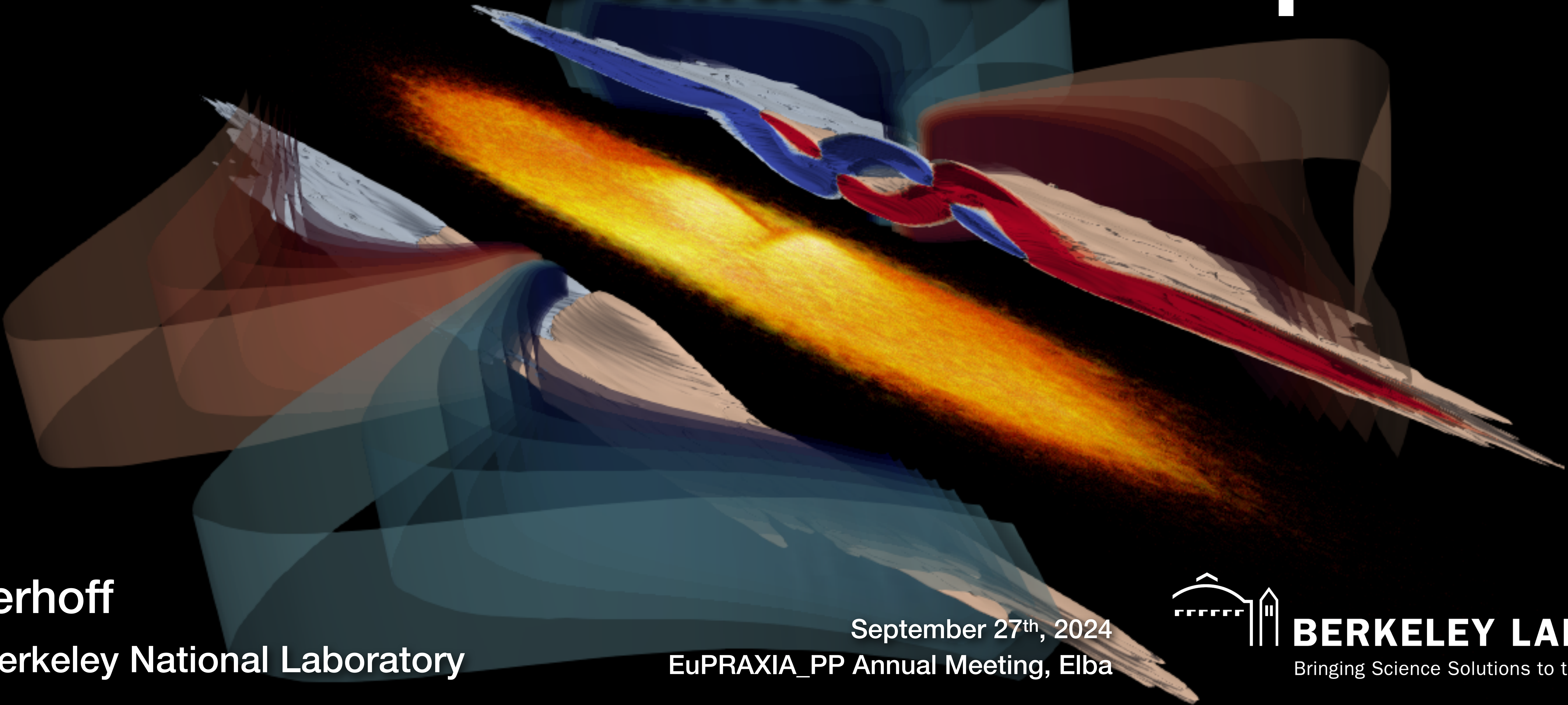
EuPRAXIA — Possible Contributions to the Linear Collider Development



Jens Osterhoff

Lawrence Berkeley National Laboratory

September 27th, 2024
EuPRAXIA_PP Annual Meeting, Elba

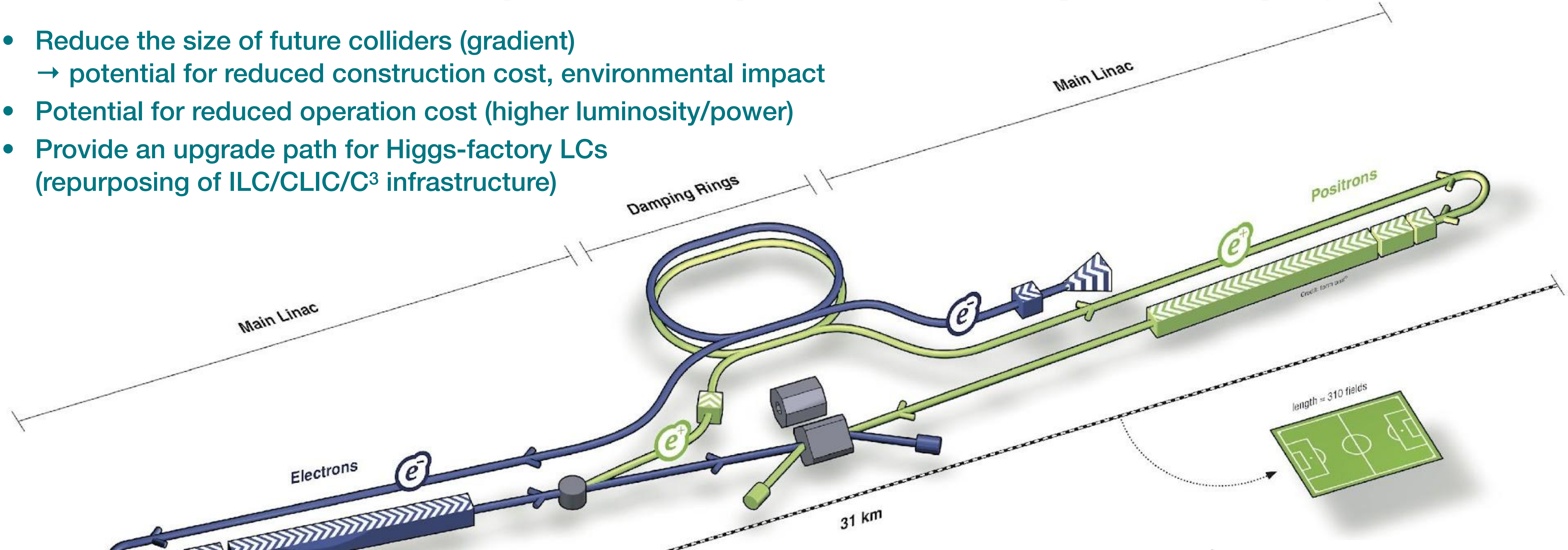
BERKELEY LAB
Bringing Science Solutions to the World

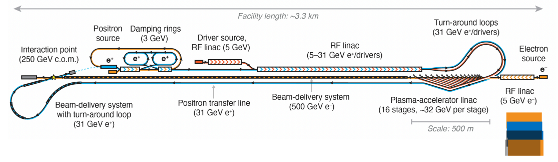
Work supported by the U.S. DOE, Office of Science, Office of High Energy Physics, under Contract No. DE-AC02-05CH11231

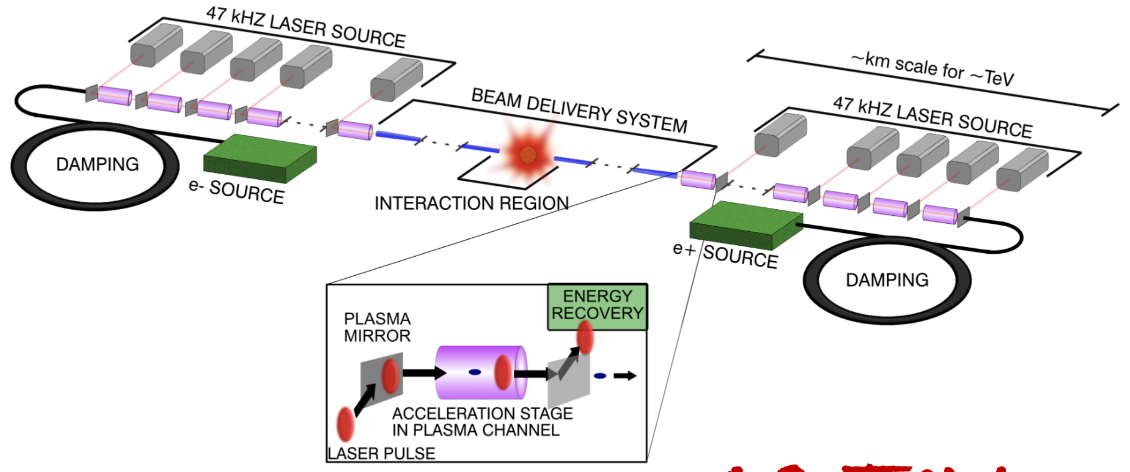
Figure credit: A. Formenti, R. Lehe (LBNL)

Plasma accelerator (> 1 GV/m) mission for particle physics

- Reduce the size of future colliders (gradient)
  → potential for reduced construction cost, environmental impact
- Potential for reduced operation cost (higher luminosity/power)
- Provide an upgrade path for Higgs-factory LCs
  (repurposing of ILC/CLIC/C^3 infrastructure)







ILC / 500 GeV / 31 km

HALHF / 250 GeV / 3.3 km

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

10 TeV

Energy Frontier Collider ~~/ 15 TeV~~ / 6.6 km*

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

*for the linac, not including the BDS

Plasma collider challenges

Beam delivery system

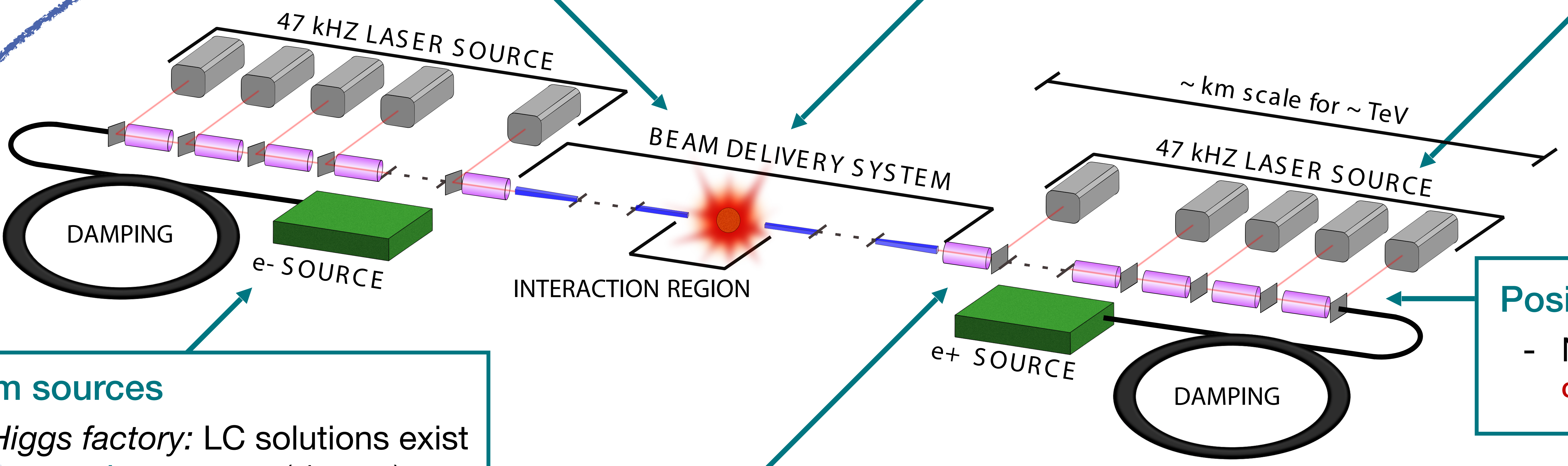
- *Higgs factory:* optimized LC designs exist
  optimizations for plasmas needed/possible?
- *10 TeV collider:* no design exists
  critical - HF designs scale poorly with energy (geo. gradient) → 20 (CLIC) to 90 (ILC) km

Interaction region

- *Higgs factory:* designed for other LCs
- *10 TeV collider:* studies critical to define collider type and machine parameters
  critical - valid codes for beam/beam studies

Driver technology

- *Beams:* technology exists in principle
  cost, gradient, efficiency, distribution optimization
- *Lasers:* do not exist, R&D paths identified
  critical - rep. rate & power, efficiency, robustness, cost
  opportunity - simple energy recovery (photovoltaics)



Positron acceleration

- No concept exists (yet) that fulfills needs
  critical - beam quality, efficiency, resilience

Beam sources

- *Higgs factory:* LC solutions exist
  opportunity - compact (cheaper) sources from plasmas
- *10 TeV collider:* undefined, potentially a key issue

Plasma stages + coupling

- Focus and key charge for our field, no roadblocks known
  critical - beam quality (incl. polarization), efficiency, stability, longevity, resilience to jitter (in time, space, and momentum), resilience to catastrophic errors (one bad shot)
- *Plasma stage:* requires demonstration of collider parameters
  + critical - rep. rates & bunch structure (CW vs. burst), power handling
- *Staging:* requires detailed concepts, additional test facilities
  + critical - driver in-/out-coupling, geometric gradient

Full system integration

- Turn components into self-consistent machine
- Optimization of the system for cost, efficiency, environmental impact, physics performance, resiliency (jitter budget)

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Plasma collider challenges — potential EuPRAXIA contributions

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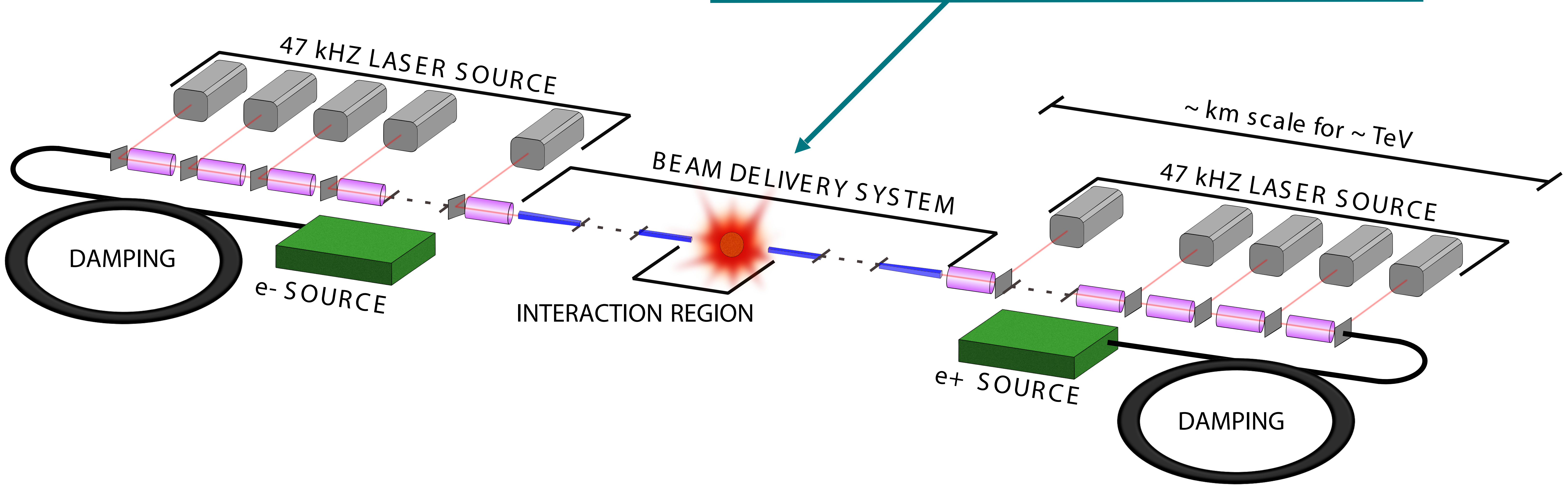
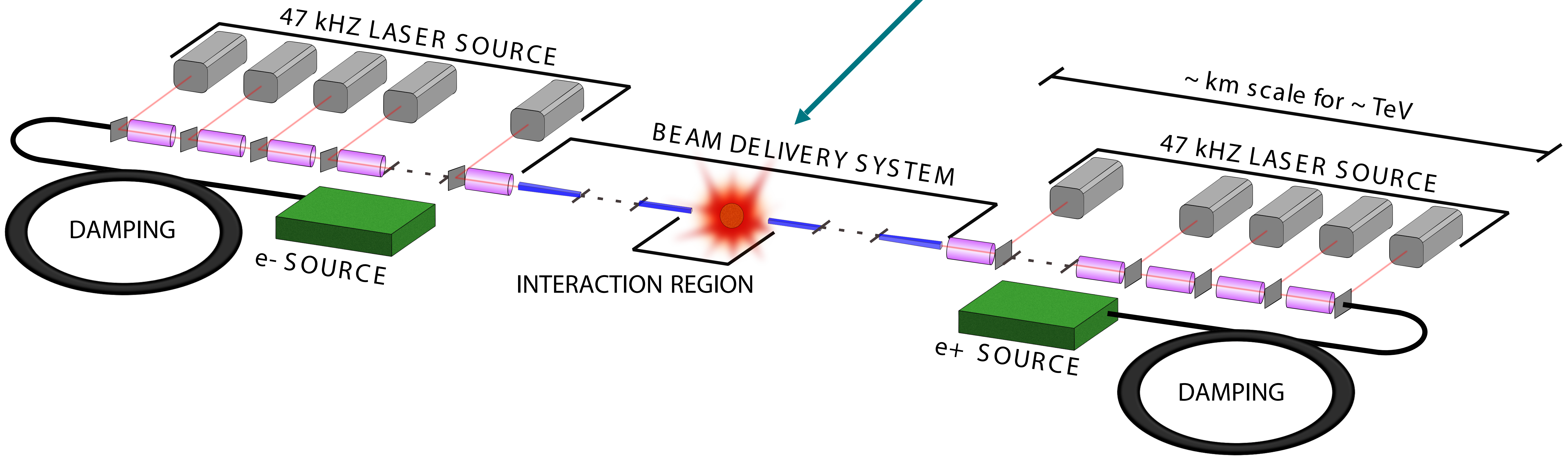


Plasma collider challenges — potential EuPRAXIA contributions

Interaction region

- *10 TeV collider:* **nonlinear QED studies**
  to verify codes for beam/beam interaction



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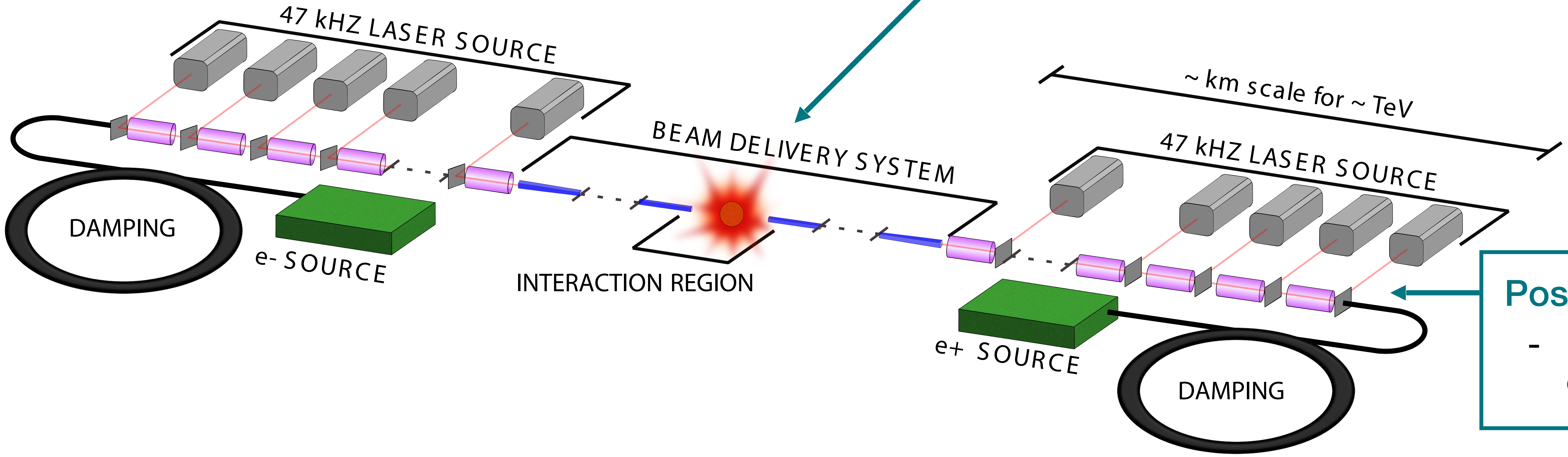

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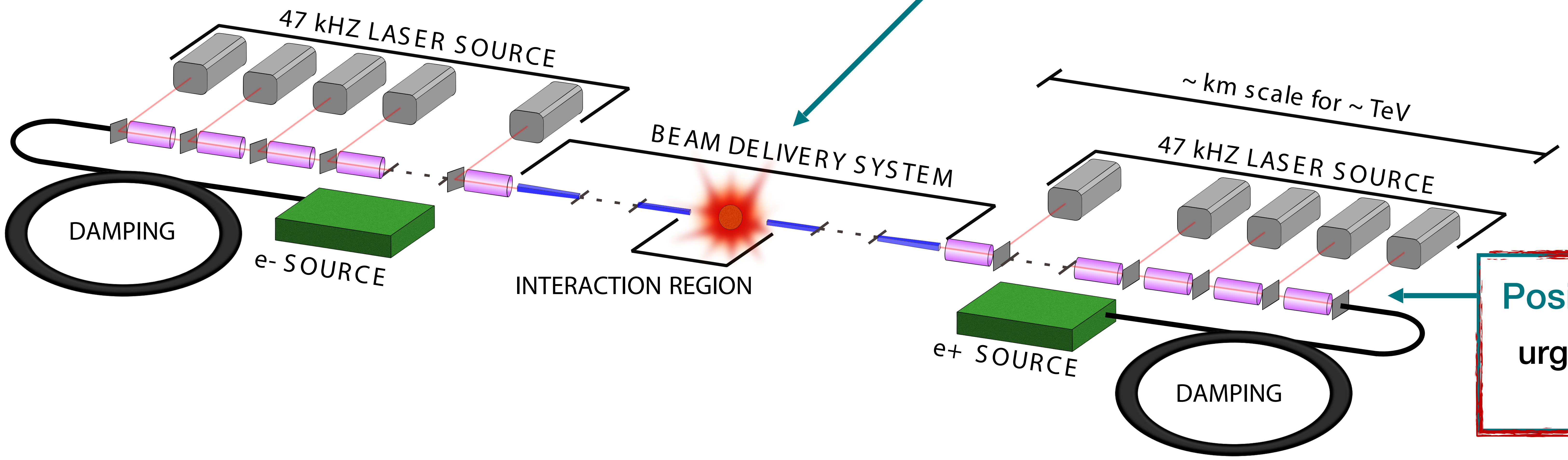

Positron acceleration

urgent need for positron test facility capabilities
→ new concepts under active R&D

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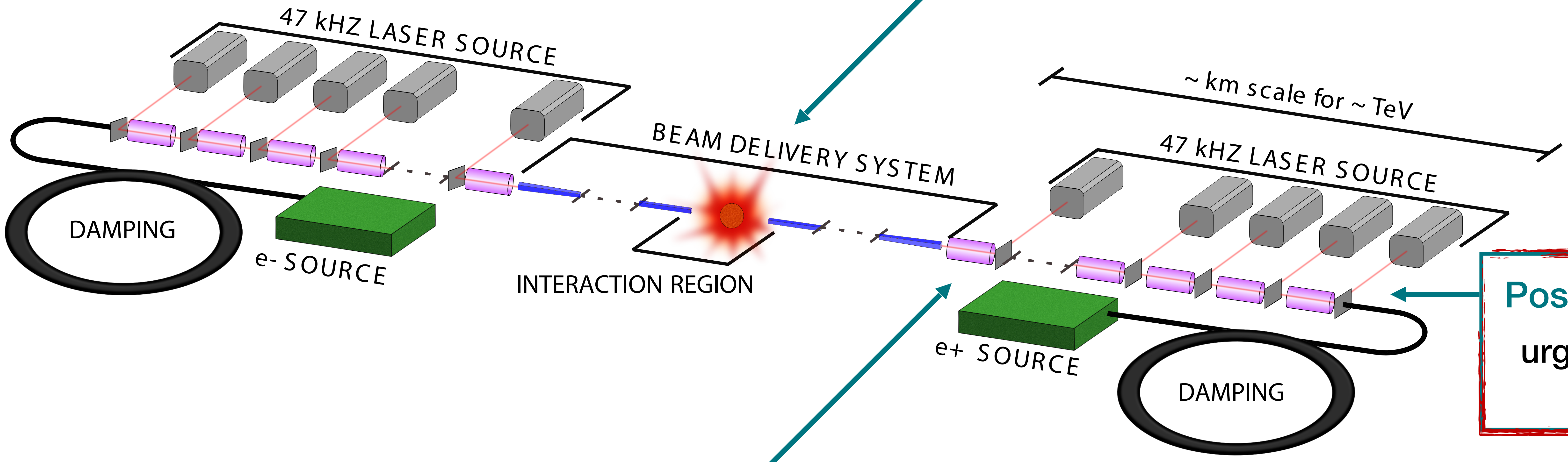

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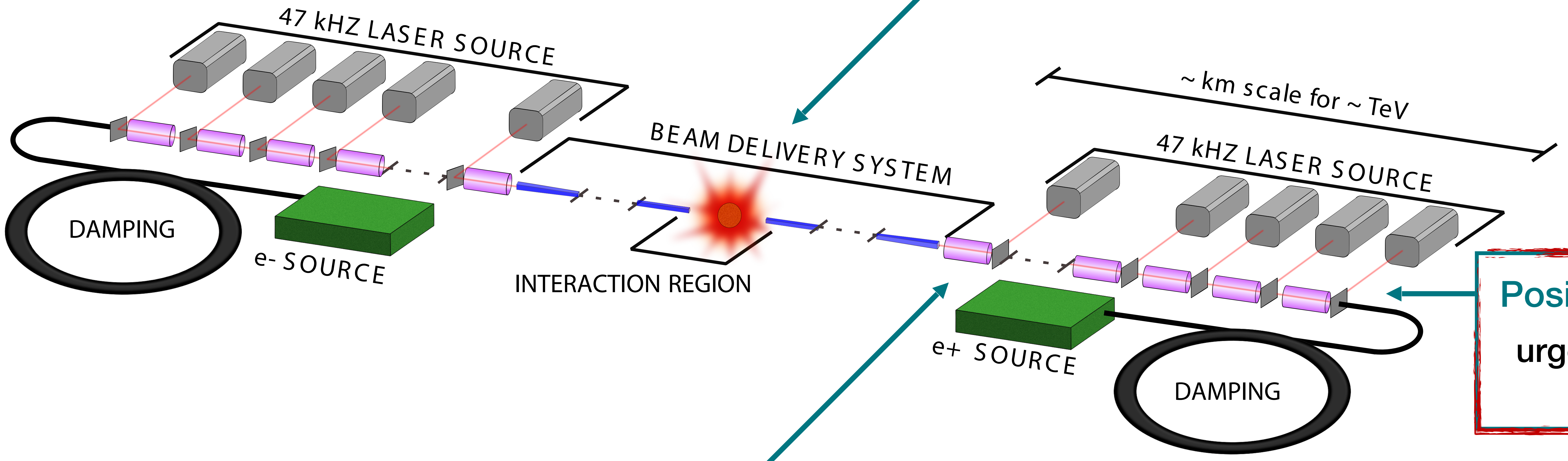

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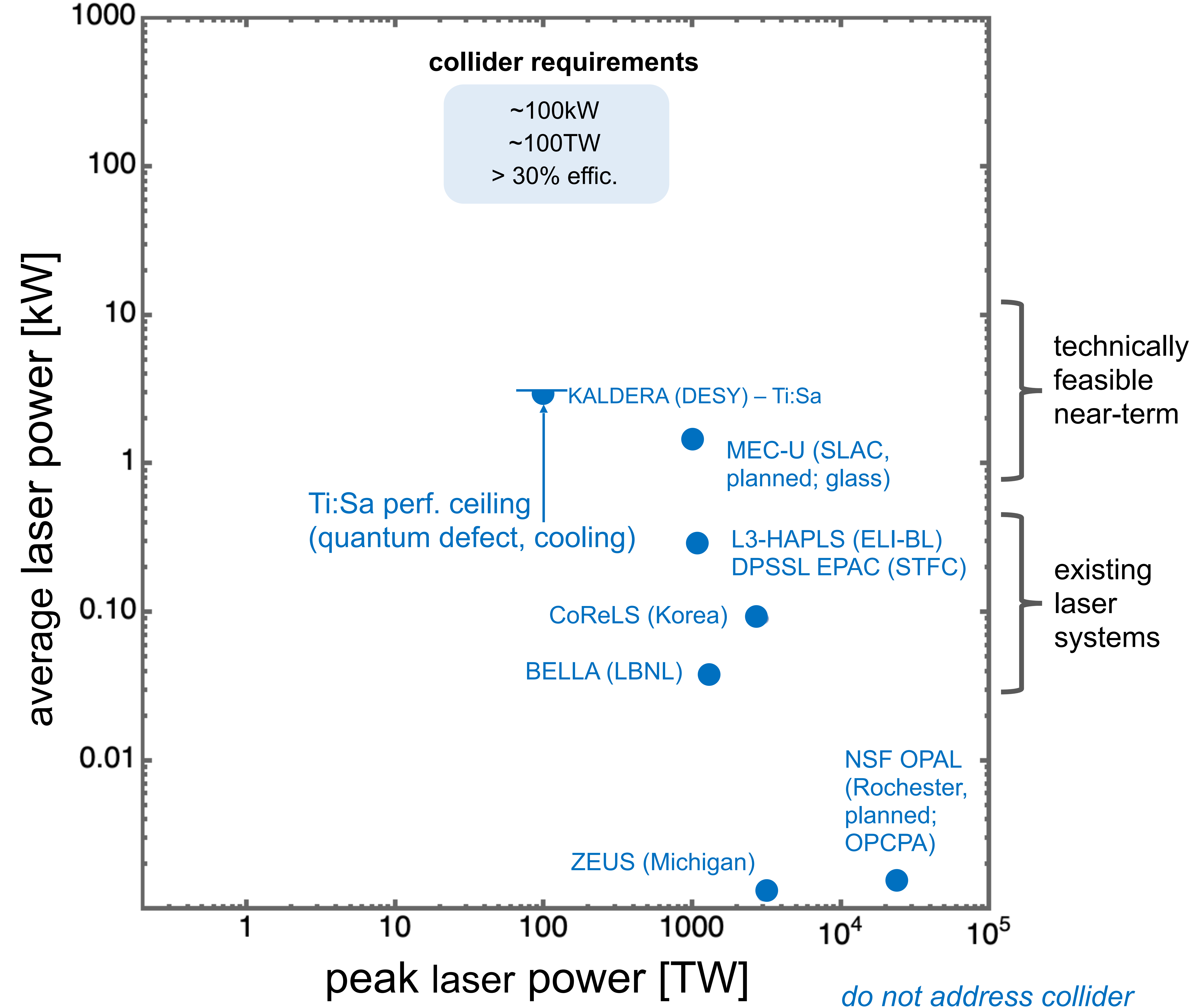
Technology R&D and critical experimental facility needs

Capability gap in laser driver technology exists for colliders

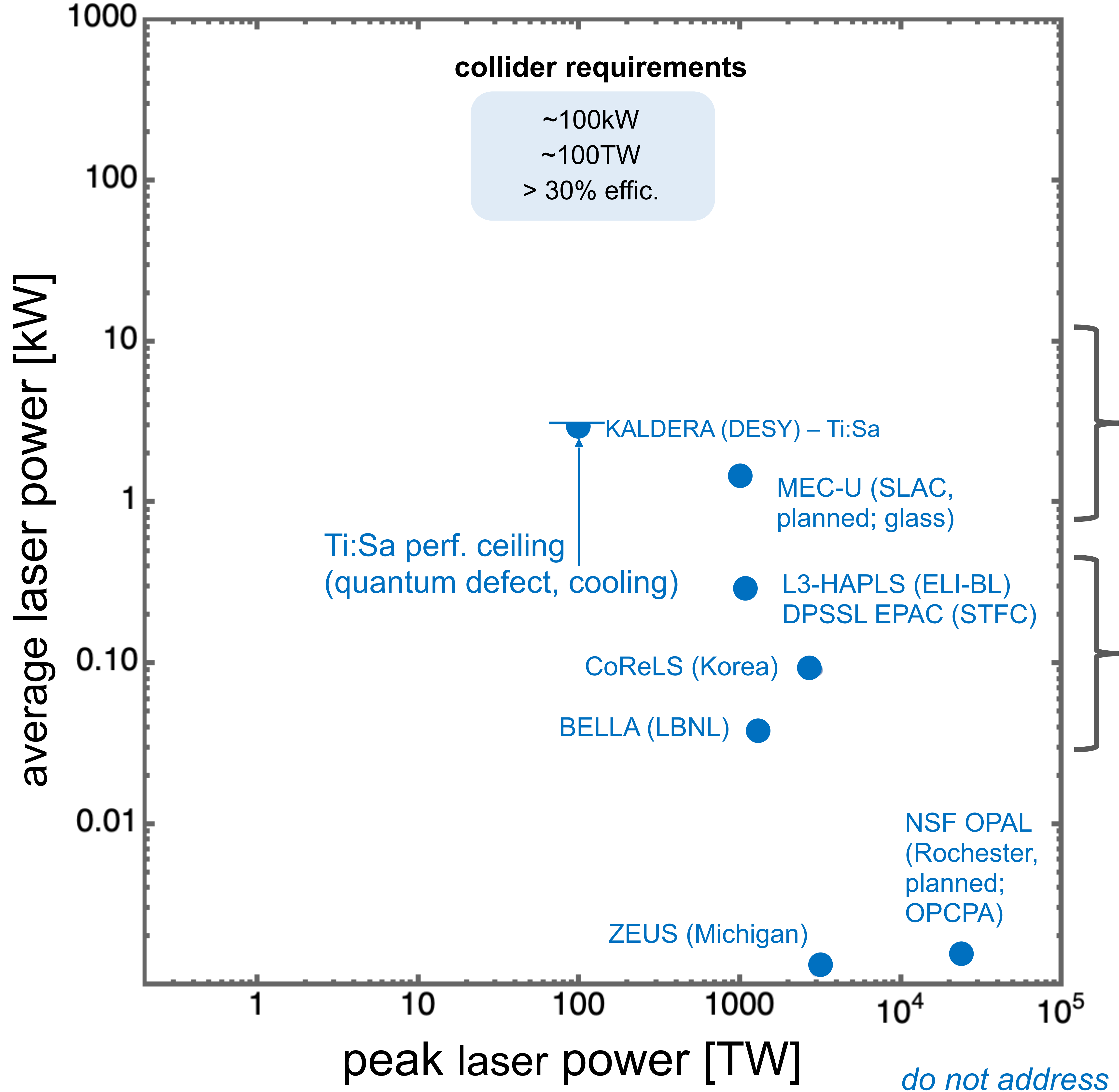


do not address collider avg. power needs

Capability gap in laser driver technology exists for colliders

Novel laser technology needed to fulfill collider demands

in repetition rate (Hz → ~50 kHz), efficiency (0.1% → 10s %)



technically feasible near-term

existing laser systems

do not address collider avg. power needs

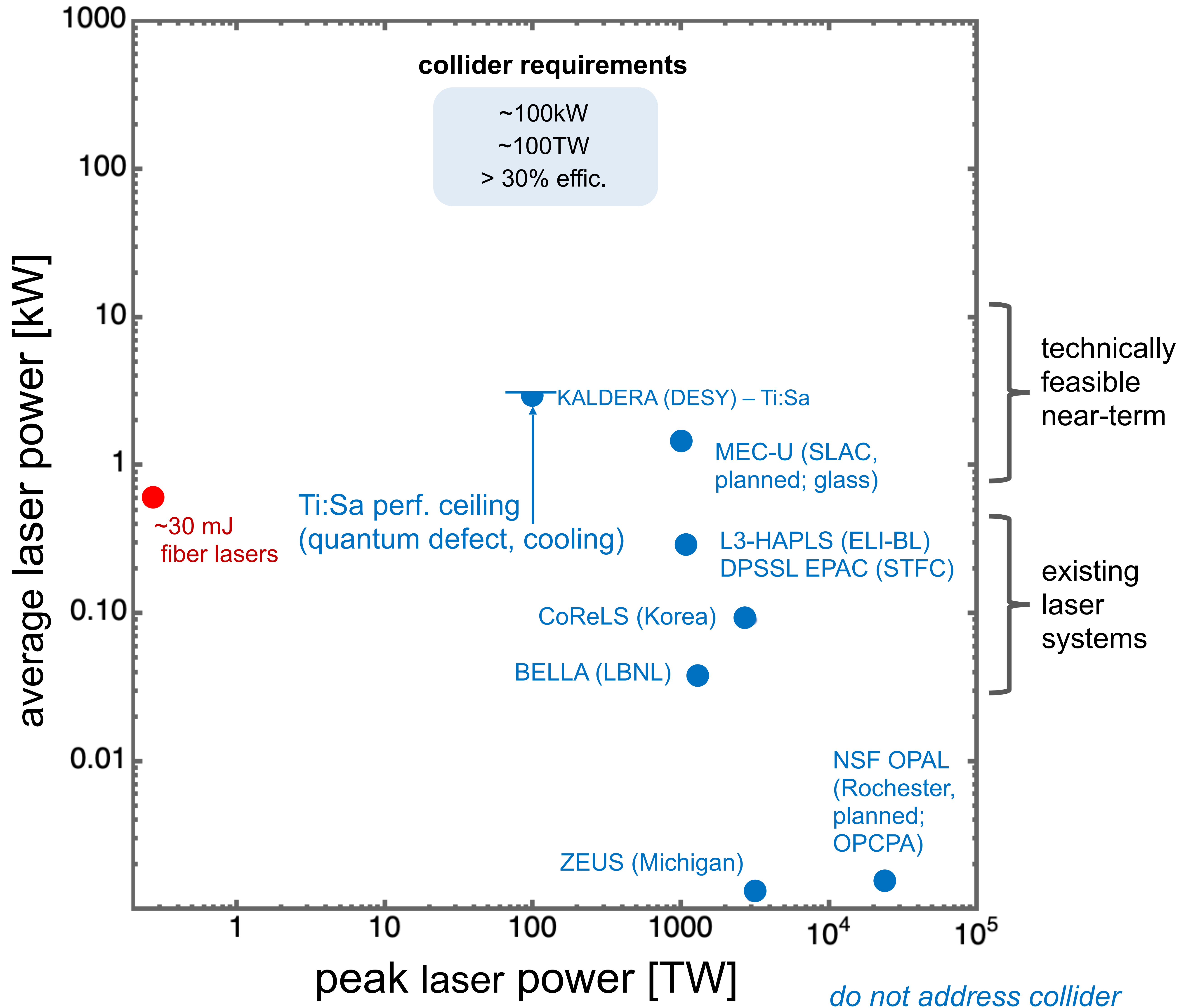
Capability gap in laser driver technology exists for colliders

Novel laser technology needed to fulfill collider demands

in repetition rate (Hz → ~50 kHz), efficiency (0.1% → 10s %)

Promising emerging laser architectures

- Cryo-cooled **Yb:YAG** (λ = 1 μm), R&D at CSU
- **Tm:YLF** (λ = 1.9 μm), R&D at LLNL
- **Coherent combination of fiber lasers** (λ = 1 μm), R&D at LBNL, Michigan, Jena, École Polytechnique
  - potential for highest efficiency
  - 1 μm to minimize # of accelerator stages
  - monolithic design for robustness, serviceability



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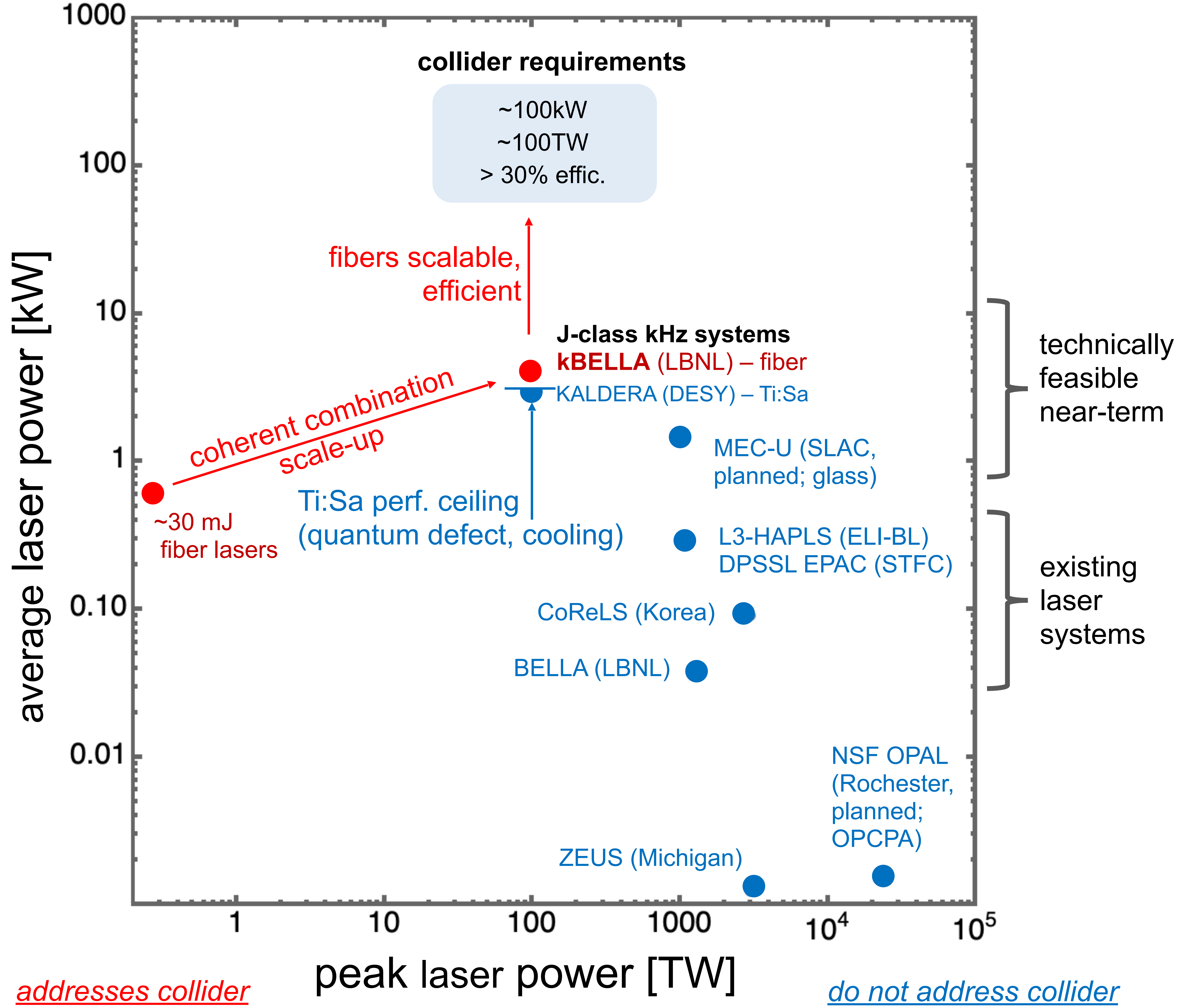
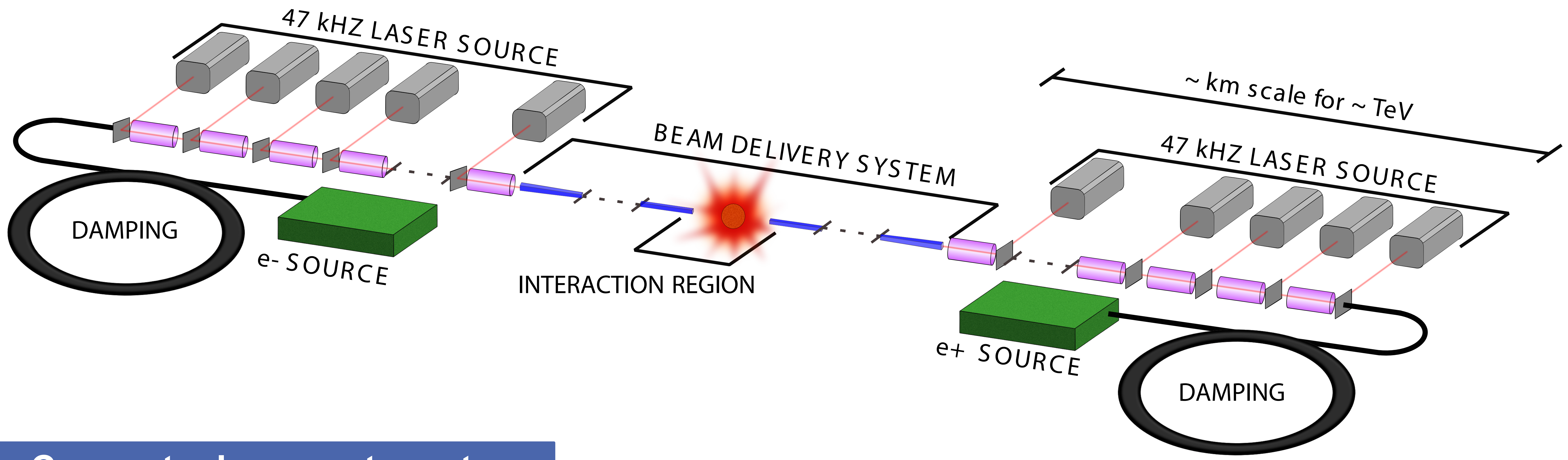


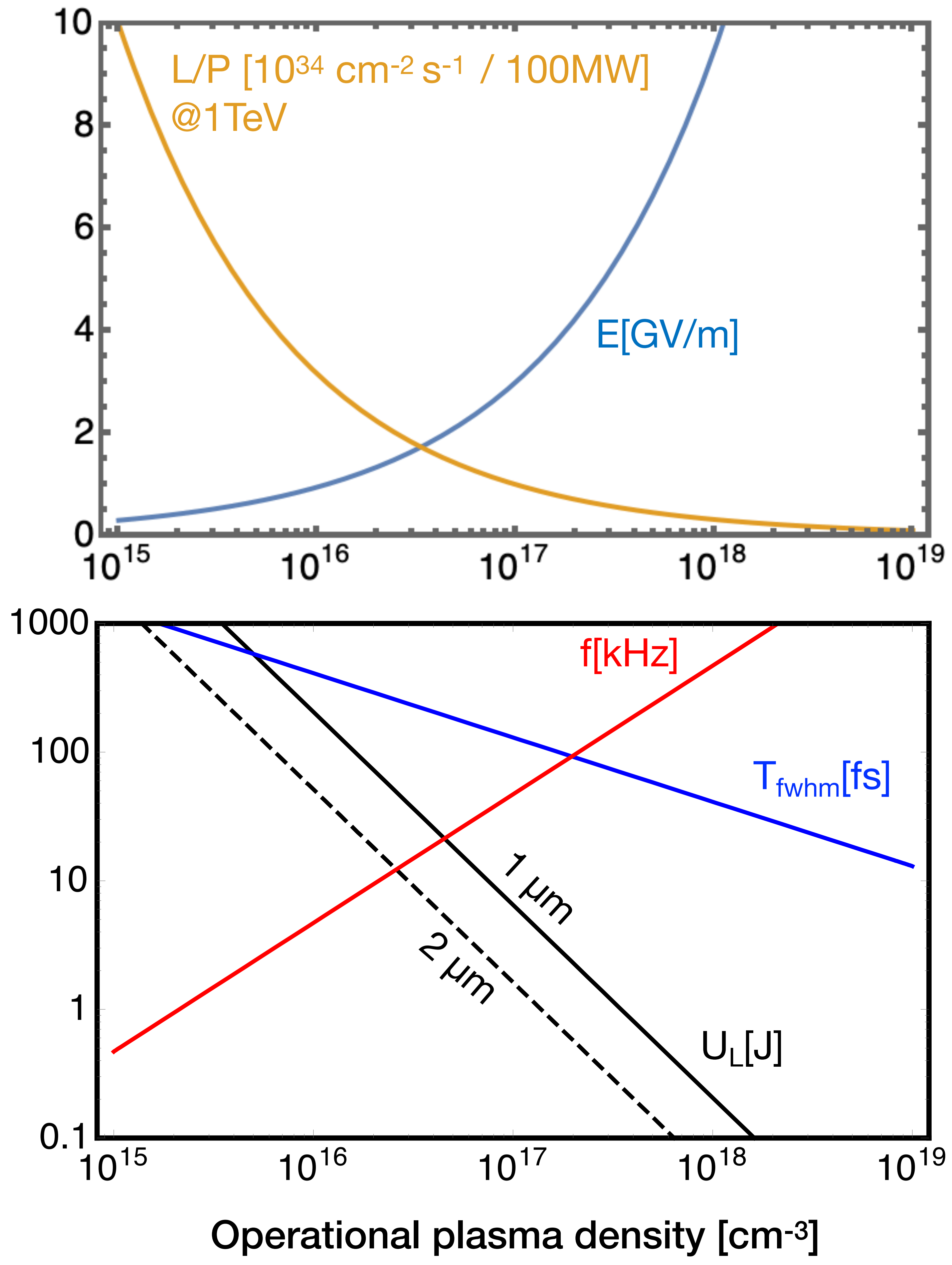
addresses collider avg. power needs

do not address collider avg. power needs

Development of a low average power demonstrator stage

LPA stage parameters for 10 TeV case in flux, likely fall within reach of EuPRAXIA 2nd pillar





Conceptual parameter set

Laser: 6.5 J energy per pulse, $\lambda = 1.0$ μm, 130 fs pulse length, **47 kHz rep. rate, 50% wall-to-laser efficiency**

Plasma: $n_0 = 10^{17}$ cm^{-3}, 1.7 m stage length, 5 GeV gain per stage

Bunch: 200 pC, 8.5 μm length

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

→ Demonstrating stage parameters
(low avg. power, varying ε_n)

Study and improve in relevant plasma cell

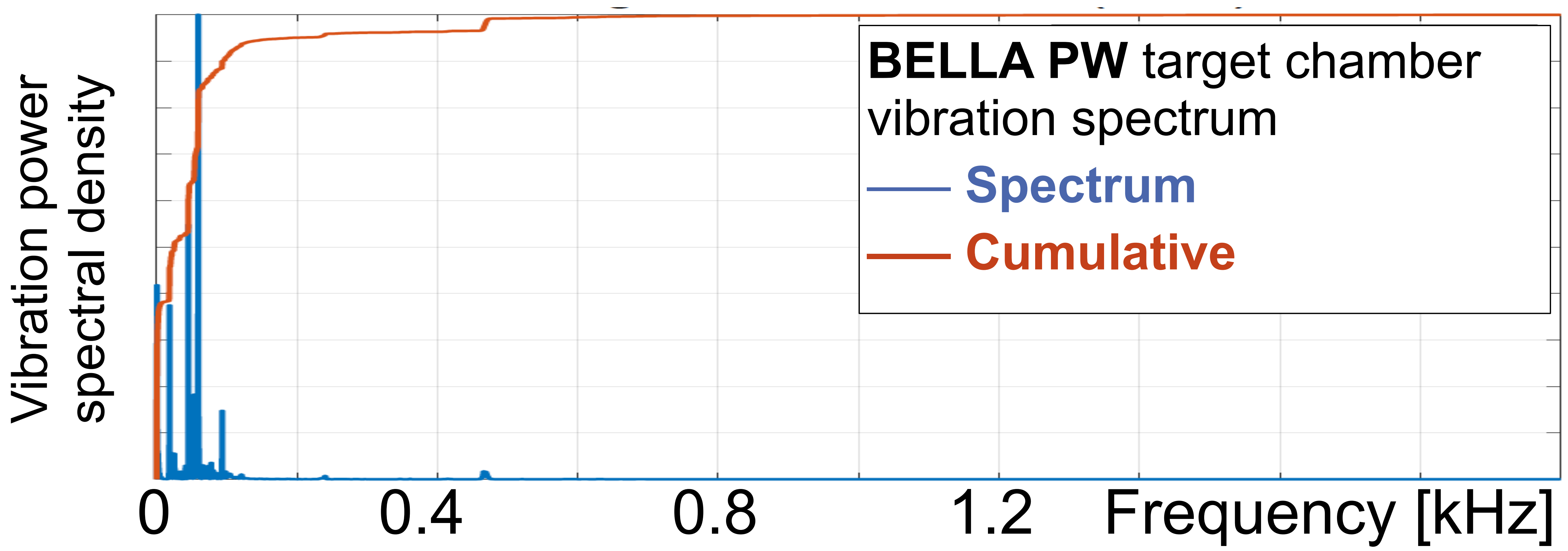
- beam quality
- efficiency
- particle spin
- stability
- longevity
- jitter effects

J. Vieira *et al.*, PRSTAB **14,** 071303 (2011)

Active correction systems for high repetition rate modules must be developed

EuPRAXIA in prime position to advance plasma stage, beam, and laser stabilization

95% of environmental vibration at up to kHz



Predominant source of vibration in LPAs
is correctable a frequencies at a few 100 Hz

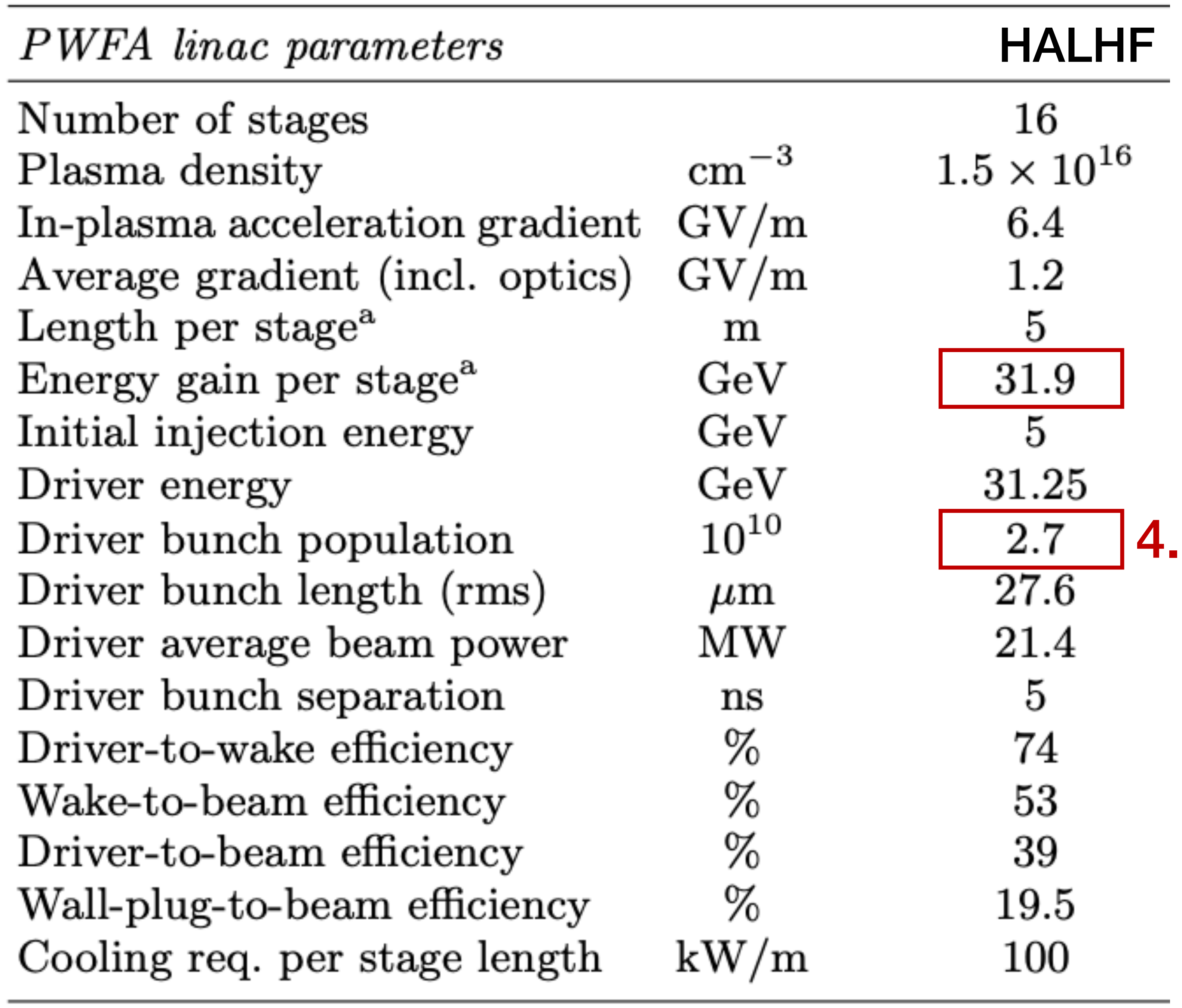
- Can be corrected at up to Nyquist frequency of laser repetition rate
- Fast correction feedbacks and controls need to be developed
- EuPRAXIA is in a prime spot to make significant contributions toward collider stability needs (still to be carefully studied)

Basic jitter considerations for plasma stages

- Wakefield amplitude [ILC: RF stability 0.3%]
  - Relatively insensitive to direct laser and plasma fluctuations:
  $$E_z \propto \frac{a_0^2 n_e^{1/2}}{(1+a_0^2/2)^{1/2}}$$
  - *But:* **phase stability critical**, e.g. fraction of max. 0.3% of $\lambda_p/2$ → max 1 fs at $n_e = 10^{17}$ cm^{-3}
- Driver - witness timing stability [see amplitude stability]
  - Beam fluctuations go down with Sqrt(N), with N the # of RF-independent accelerator modules (w/o accounting for chromatic transport effects)
  - ILC: 0.85 GeV per RF unit; plasma LC: energy gain/module 10 GeV → **3.4x higher req. vs ILC**
  - Can be mitigated by Lindstrøm scheme
- Transverse driver - witness positioning in wake
  - Has to be a fraction of witness spot size → emittance growth in matched wakefield
  - Matched **beam size in 1 nm** range for multi-TeV!
  - Mitigation: quasi-linear wakes/hollow channels?

PWFA stages for colliders likely to escape EuPRAXIA parameter space

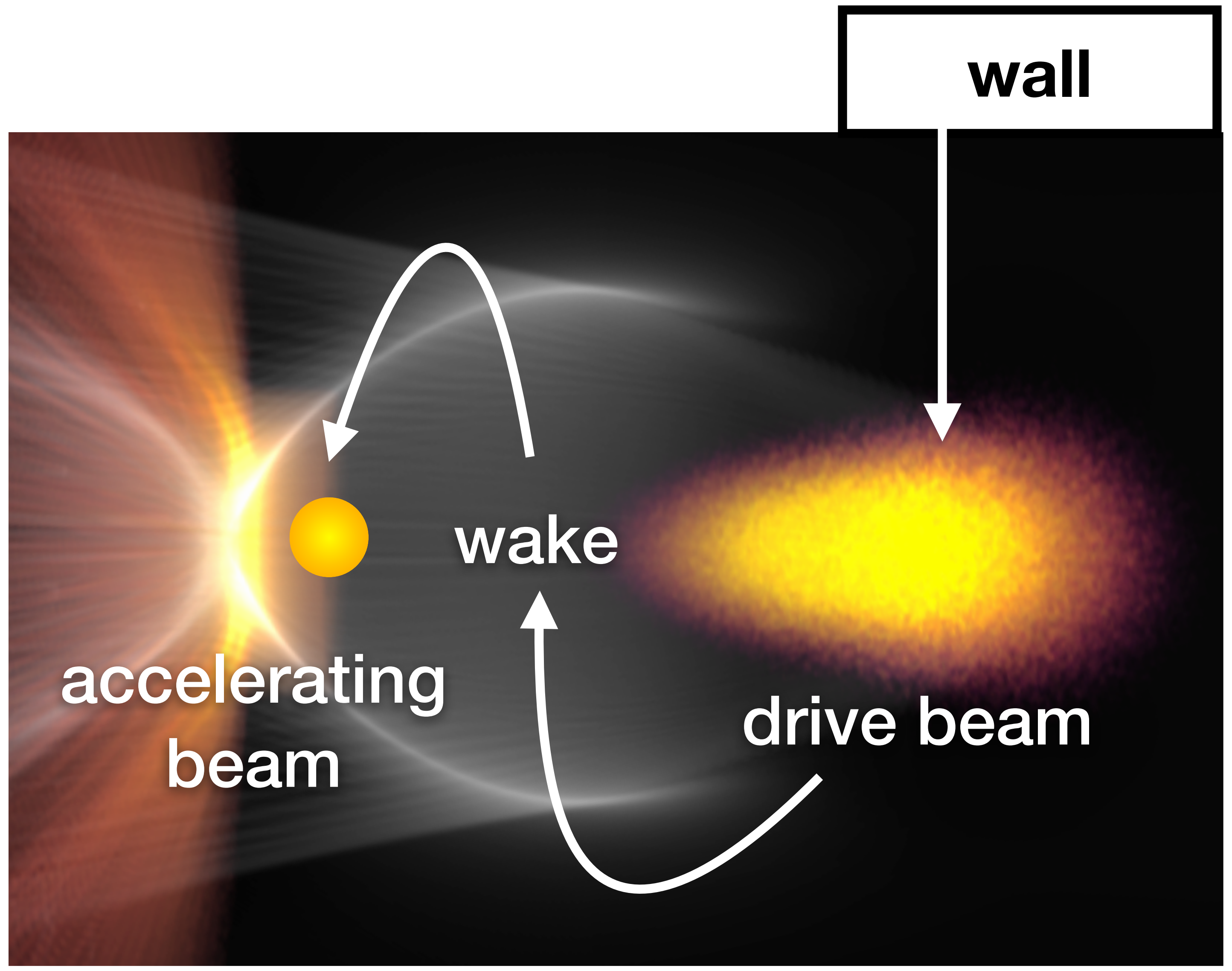
General beam-driven module R&D still of high interest for gaining credibility for complex applications

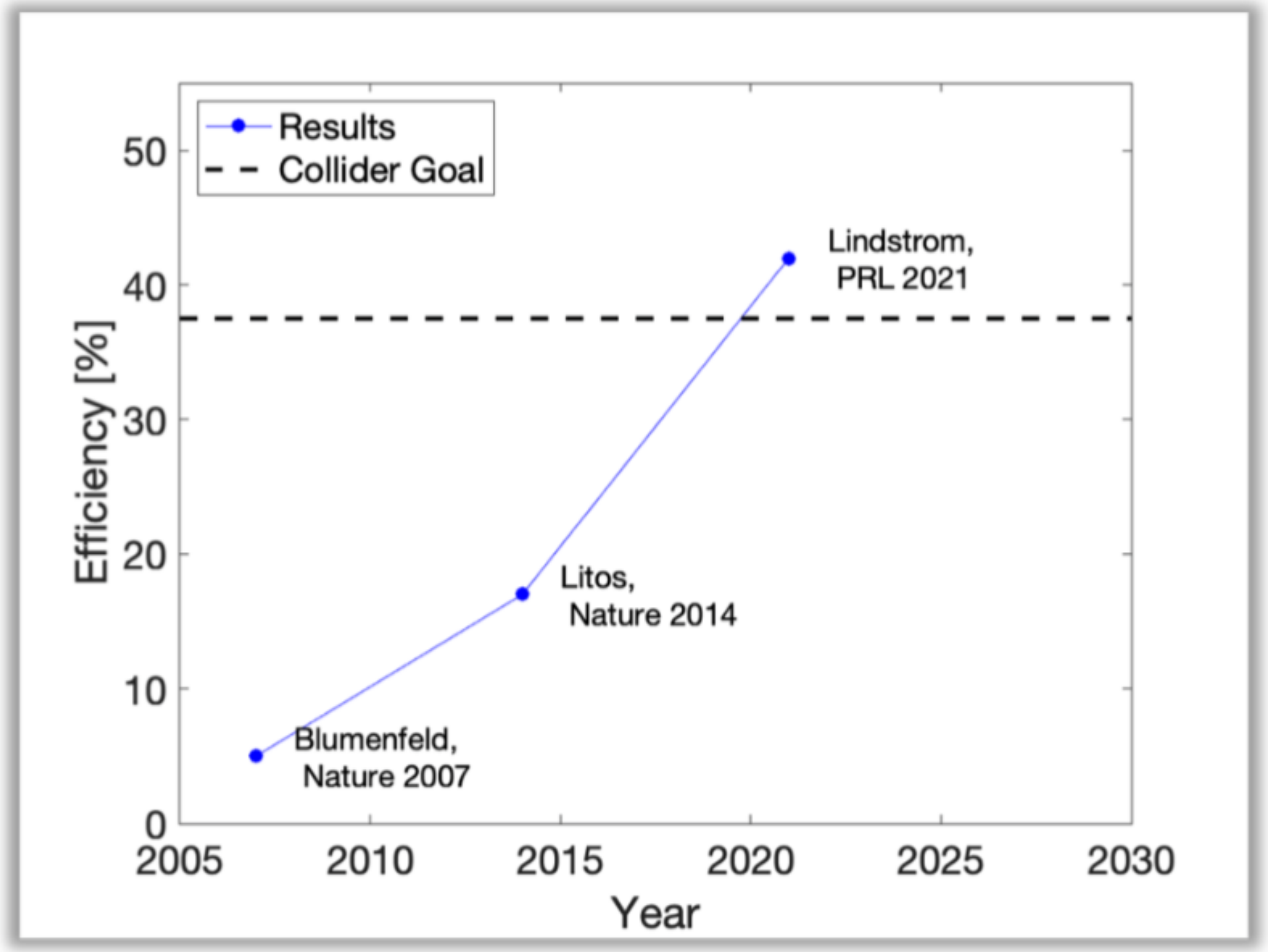


PWFA linac parameters		HALHF
Number of stages		16
Plasma density	cm^{-3}	1.5×10^{16}
In-plasma acceleration gradient	GV/m	6.4
Average gradient (incl. optics)	GV/m	1.2
Length per stage[a]	m	5
Energy gain per stage[a]	GeV	31.9
Initial injection energy	GeV	5
Driver energy	GeV	31.25
Driver bunch population	10^{10}	2.7
Driver bunch length (rms)	μm	27.6
Driver average beam power	MW	21.4
Driver bunch separation	ns	5
Driver-to-wake efficiency	%	74
Wake-to-beam efficiency	%	53
Driver-to-beam efficiency	%	39
Wall-plug-to-beam efficiency	%	19.5
Cooling req. per stage length	kW/m	100

4.4 nC

- Energy gain per stage / bunch charge outside of EuPRAXIA reach
- General advancements in beam-driven stage R&D important for field:
  - large energy gain / gradient
    + beam-quality preservation
    + high driver-to-witness efficiency
    + high stability / low jitter

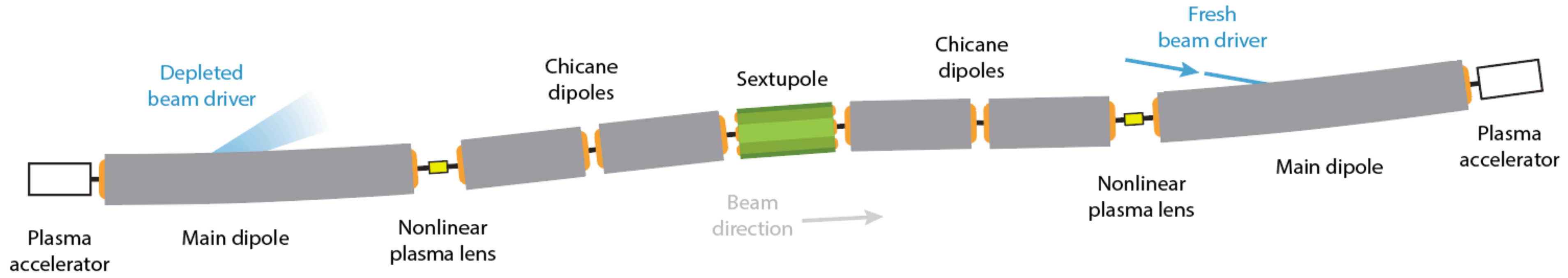




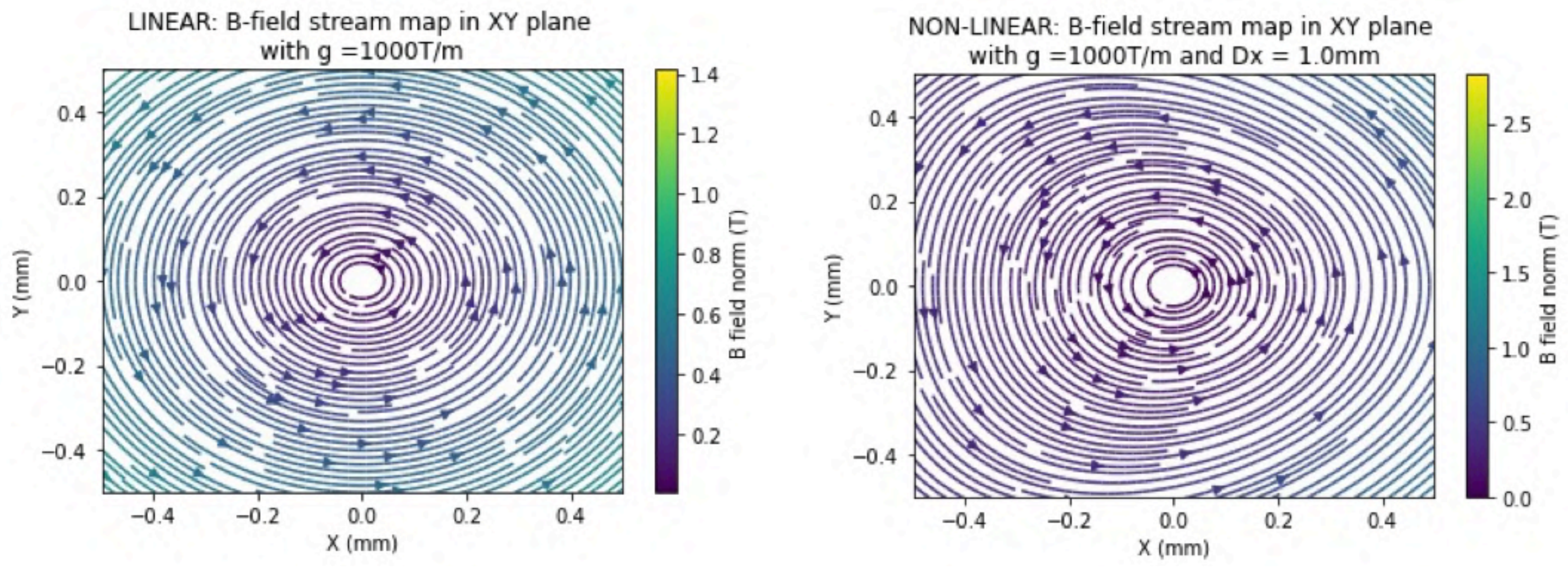
Achromatic transport, nonlinear APLs for staging to be tested

PWFA staging test facility urgently required — can EuPRAXIA take on that role?

PWFA staging concept for HALHF

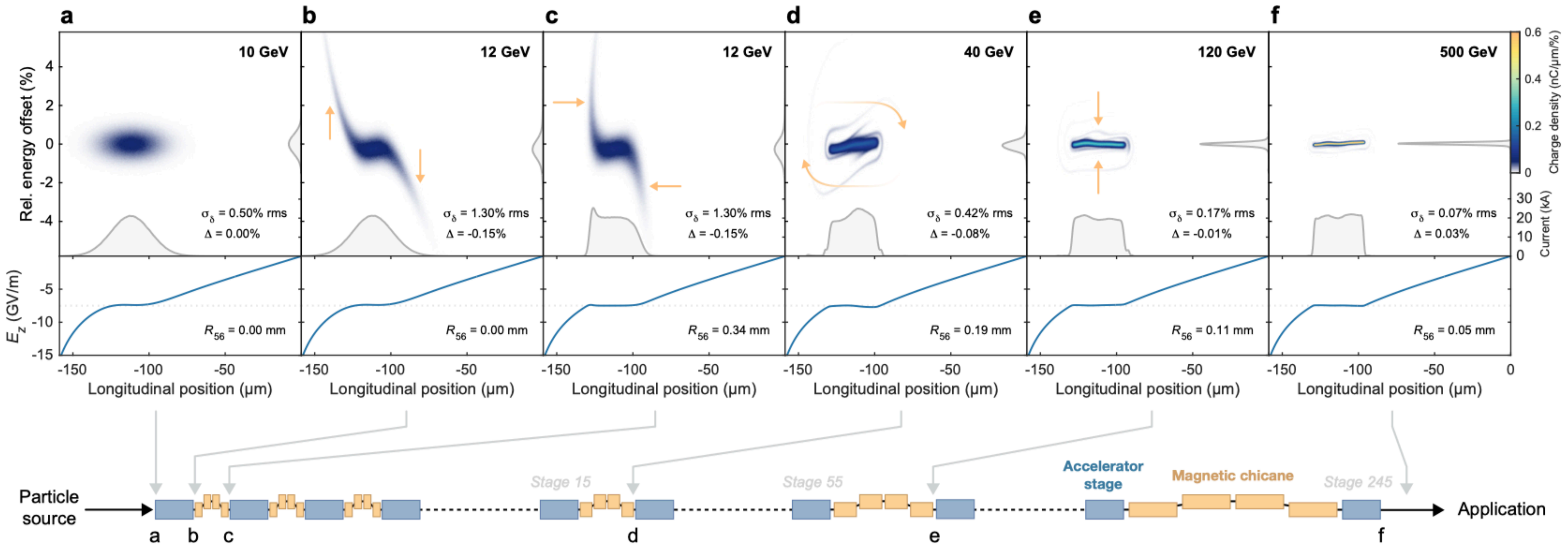


C.A.Lindstrøm,
SPARTA ERC Project



B-fields in nonlinear plasma lens. Credit: P. Drobniak

Temporal self-correction in staging



C.A. Lindstrøm, arXiv:2104.14460 (2021)

Challenges

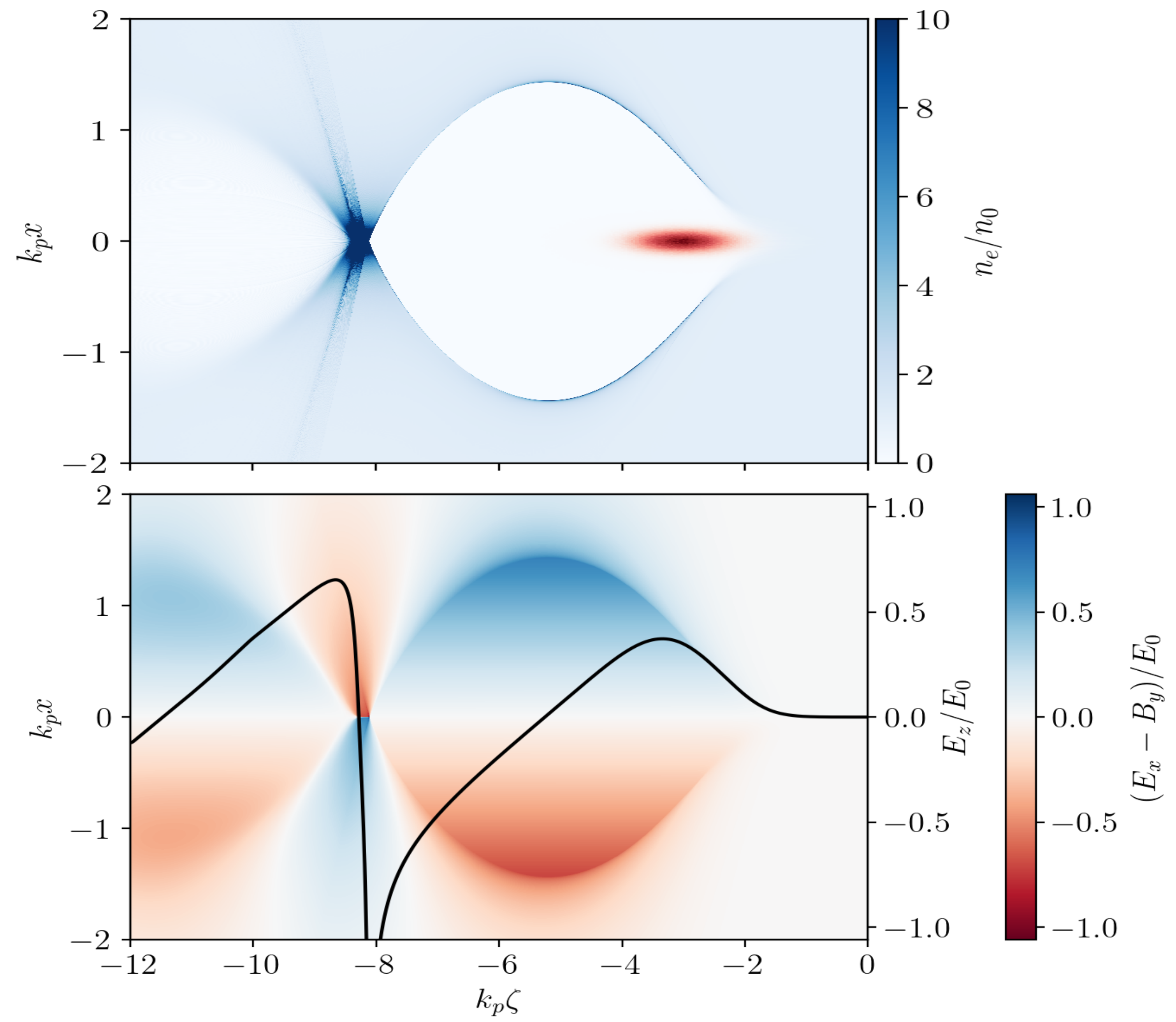
- In- and out-coupling of drivers
- Synchronization of drivers at fs-scale
- Isochronicity (R_{56}) cancellation/control (for correct beam loading)
- Emittance preservation between stages:
  - Matching of beta function for all energies
  - Transverse alignment and stability
  - Dispersion cancellation
  - Coulomb scattering
- Driver distribution scheme
- CSR management
- Compactness (for a TeV/km average accelerating gradient)
- (Transverse) tolerances & jitter
- Synchrotron rad. in NL APL → energy spread increase

New promising positron acceleration concepts are emerging

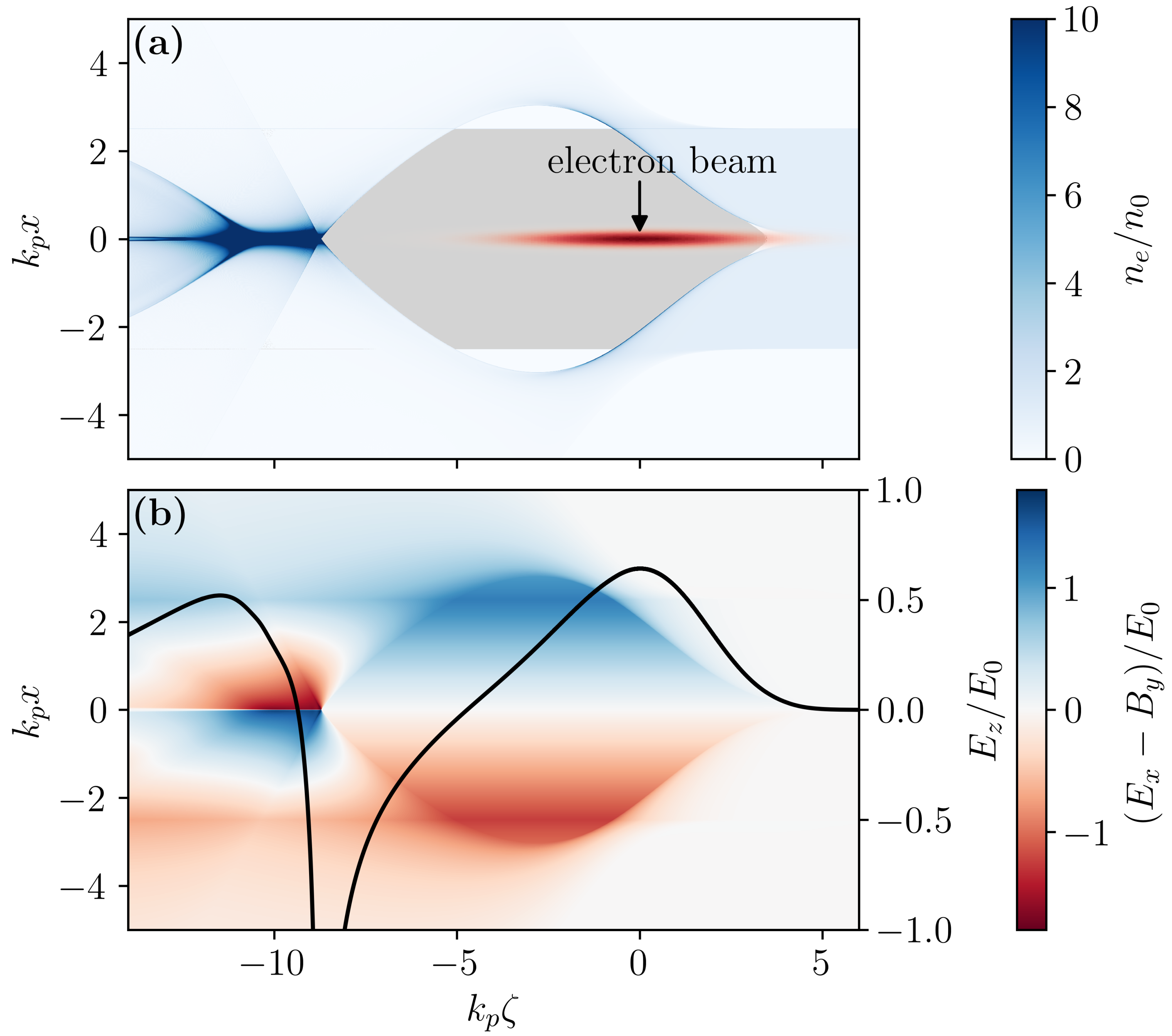
New plasma-based schemes could provide pathway to high beam quality, stability, high efficiency

→ Need a test facility!

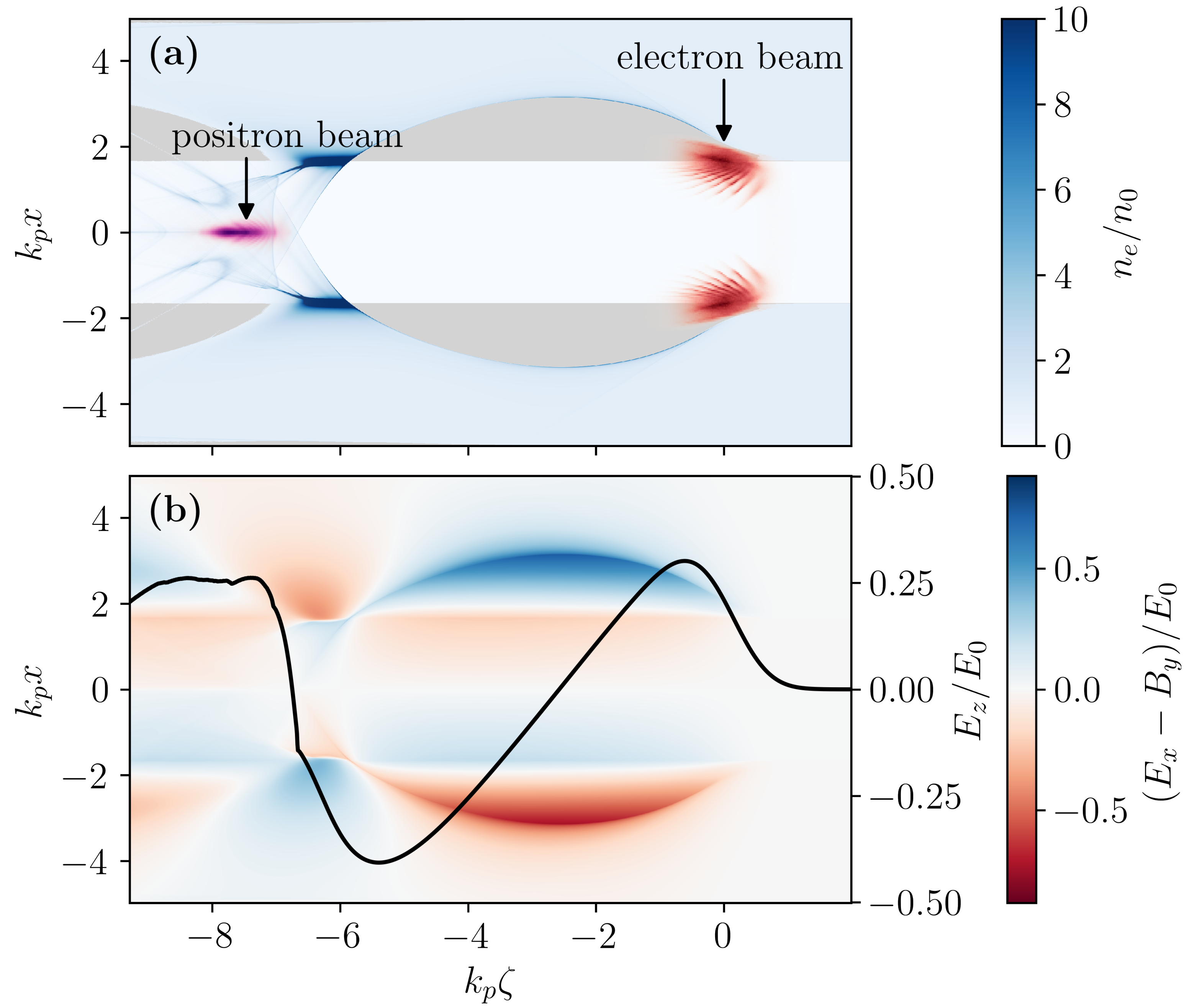
Homogeneous plasma
→ positron acceleration is hard



Finite plasma channels and electron filaments



Asymmetric drive beams in a hollow core plasma channel



More concepts:
Lotov, PoP 14, 023101 (2007)
Zhou et al. arXiv:2211.07962v1 (2022)
Wang et al. arXiv. 2110.10290 (2021)
Liu et al., PRAppl 19, 044048 (2023)

Finite plasma channels:
Diederichs et al., PRAB 22, 081301 (2019)
Diederichs et al., PRAB 23, 121301 (2020)
Diederichs et al. PoP 29, 043101 (2022)
Diederichs et al. PRAB 25, 091304 (2022)

Hollow core plasma channels:
Zhou et al., PRL 127, 174801 (2021)
Zhou et al., PRAB 25, 091303 (2022)
Silva et al., PRL 127, 104801 (2021)

Physics verification and simulation code benchmarking

Emittance mixing of flat beams needs to be explored in experiment

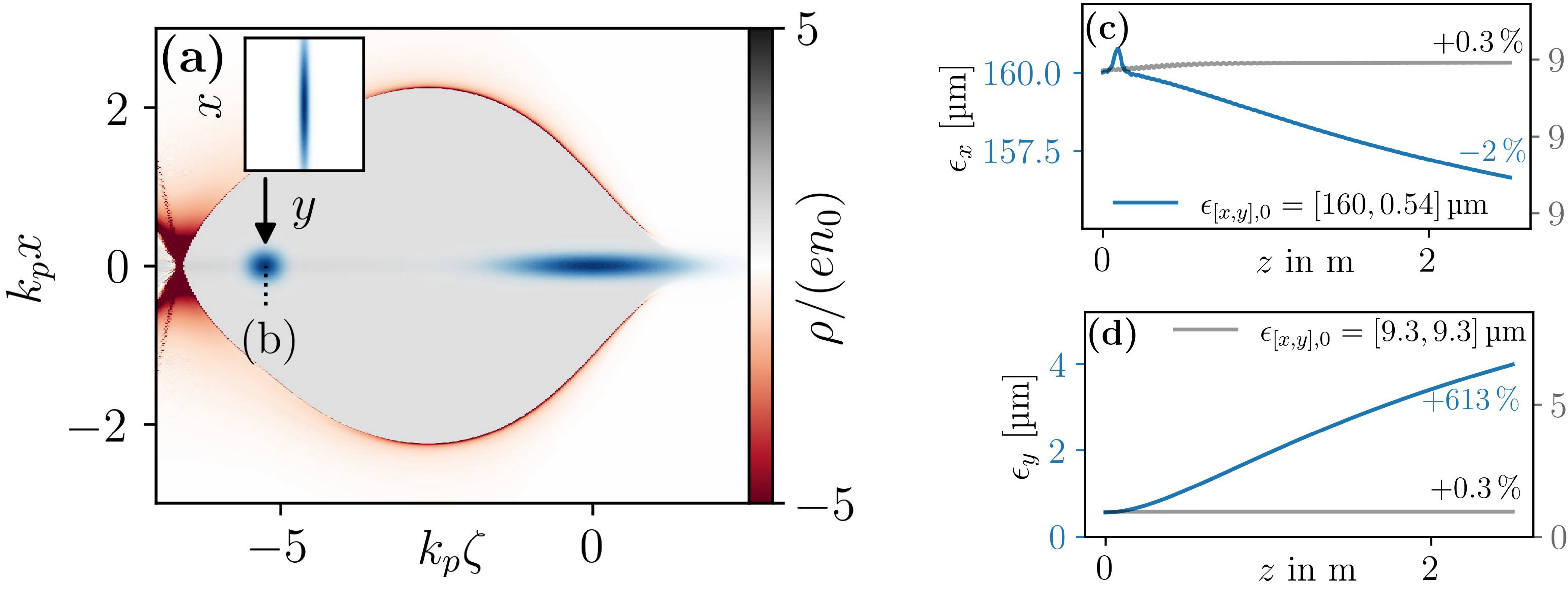
Transverse wakefields with ion motion

$$\frac{E_x - B_y}{E_0} = \frac{k_p x}{2}\left[1 + \alpha_x H\left(\frac{r^2}{2L_x^2}\right)\right]$$

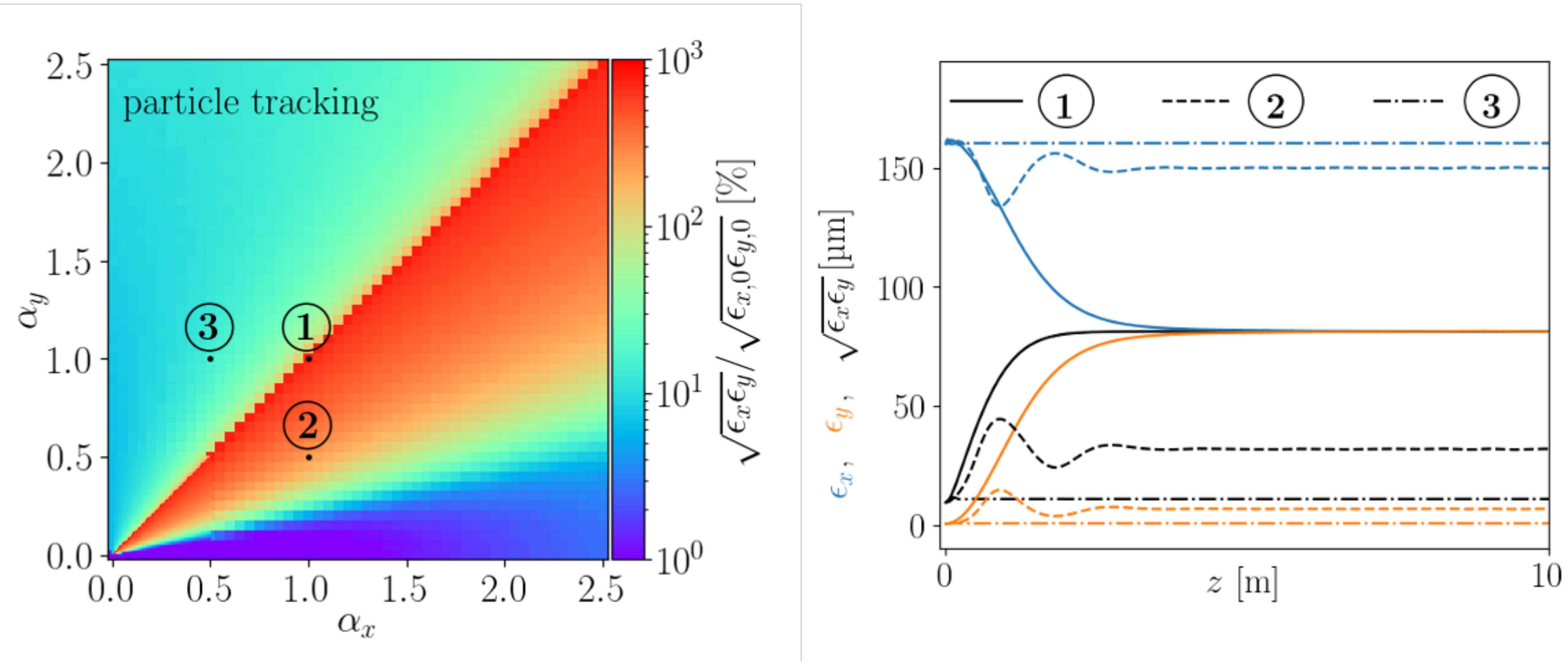
$$\frac{E_y + B_x}{E_0} = \frac{k_p y}{2}\left[1 + \alpha_y H\left(\frac{r^2}{2L_y^2}\right)\right]$$

Coupled nonlinearity: $r = \sqrt{x^2 + y^2}$
facilitates x-y coupling and emittance growth

C. Benedetti *et al.*, **PRAB** 20, 111301 (2017)



- **NL trans. wakefields couple motion in trans. planes**
  → can lead to emittance exchange
  → sources: ionization, ion motion, trans. n_e gradients, …
- Most severe for resonant betatron motion (case ①)
- Breaking resonance mitigates beam-quality degradation
- **Flat drive beams** (Nonlinear force is non-axisym.), **laser drivers** (ion motion is negligible) mitigate effect
- NL originating from witness an unsolved challenge



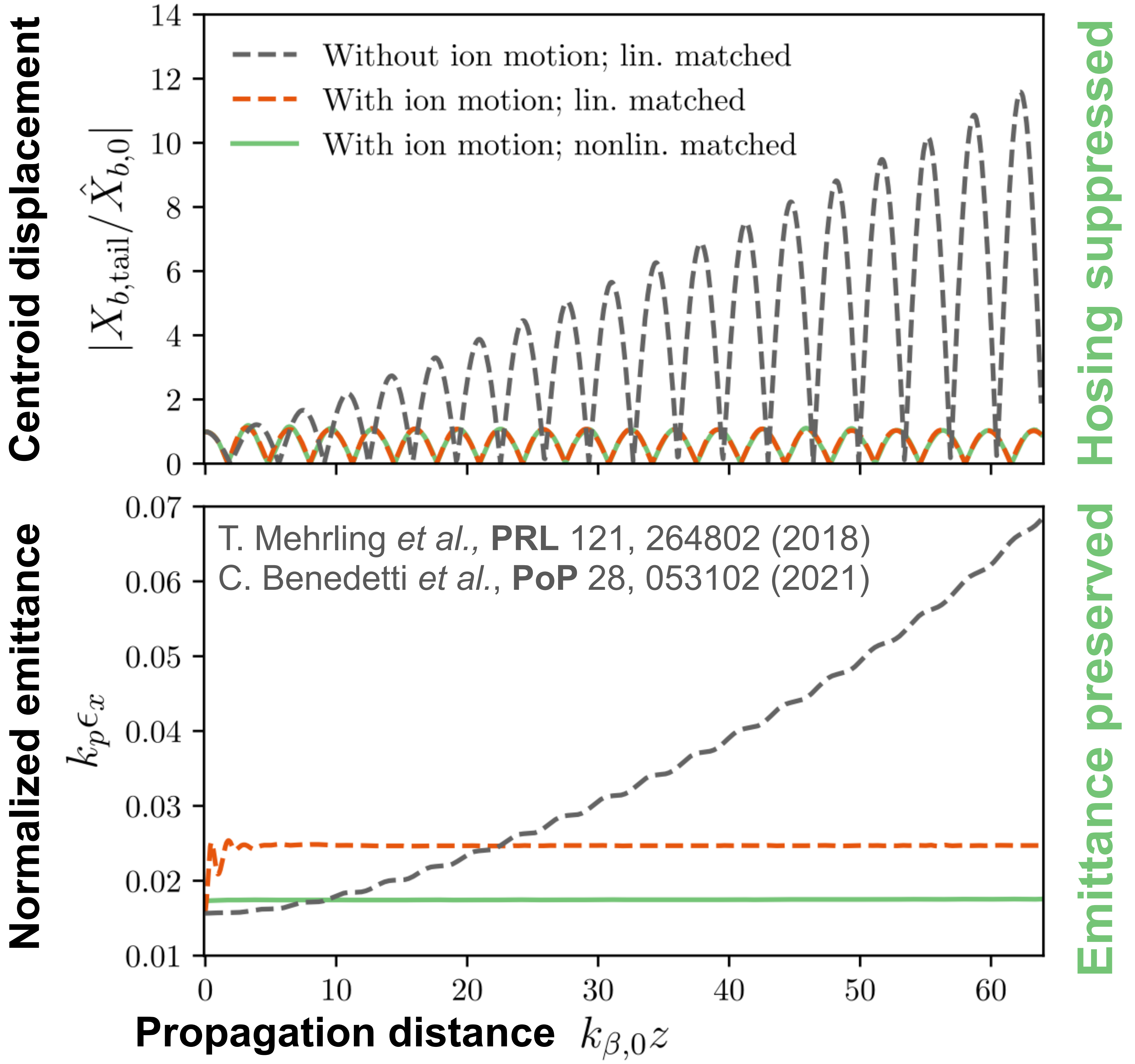
S. Diederichs *et al.*, arXiv:2403.05871, under review (2024)

Critical beam dynamics challenges for colliders have been overcome: mitigating hosing instability and beam scattering effects in simulations

Experimental verification of simulations/physics required, can EuPRAXIA help?

Hosing/BBU instability: high efficiency and stability in plasma facilitated by ion motion

- **via BNS damping:** requires large (~10%) chirp owing to strong beam loading – transport challenges
- **with head-to-tail density variation:** naturally created by ion motion



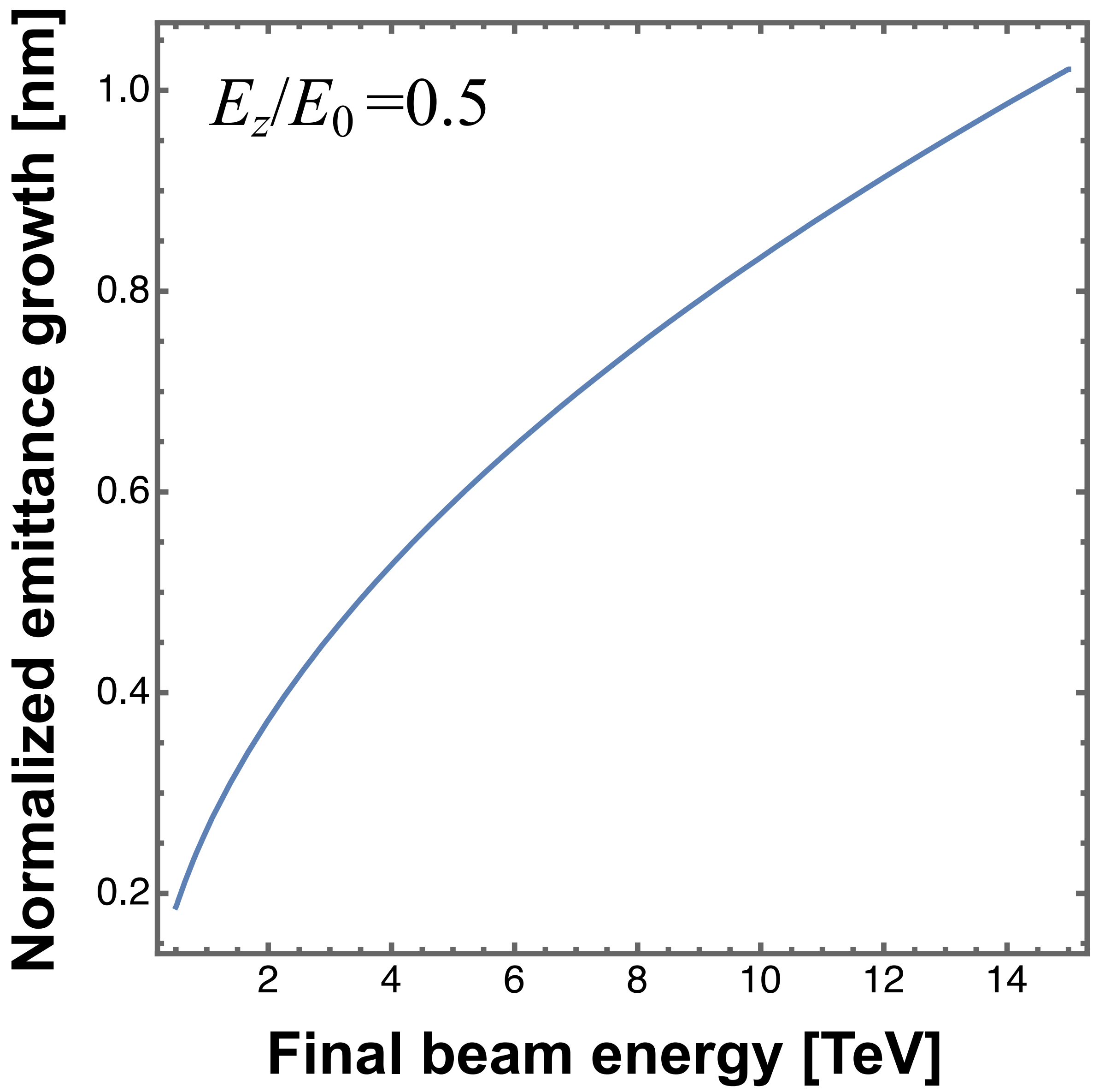
T. Mehrling *et al.*, **PRL** 121, 264802 (2018)
C. Benedetti *et al.*, **PoP** 28, 053102 (2021)

Beam scattering in plasma negligible: sub-nm normalized emittance growth for a TeV-scale collider

$$\frac{d\epsilon_n}{dz} \simeq \frac{\gamma}{2k_\beta}\frac{d\langle\theta_x^2\rangle}{dz} \qquad \Delta\epsilon_n = \frac{\sqrt{2}r_e Z}{(E_z/E_0)}\ln\left(\frac{r_{\max}}{r_{\min}}\right)\gamma_f^{1/2} \sim r_e\gamma_f^{1/2}$$

↑ Strong focusing suppresses emittance growth

- Emittance growth (very) weakly dependent on plasma density (reduction in density ↔ increase length)

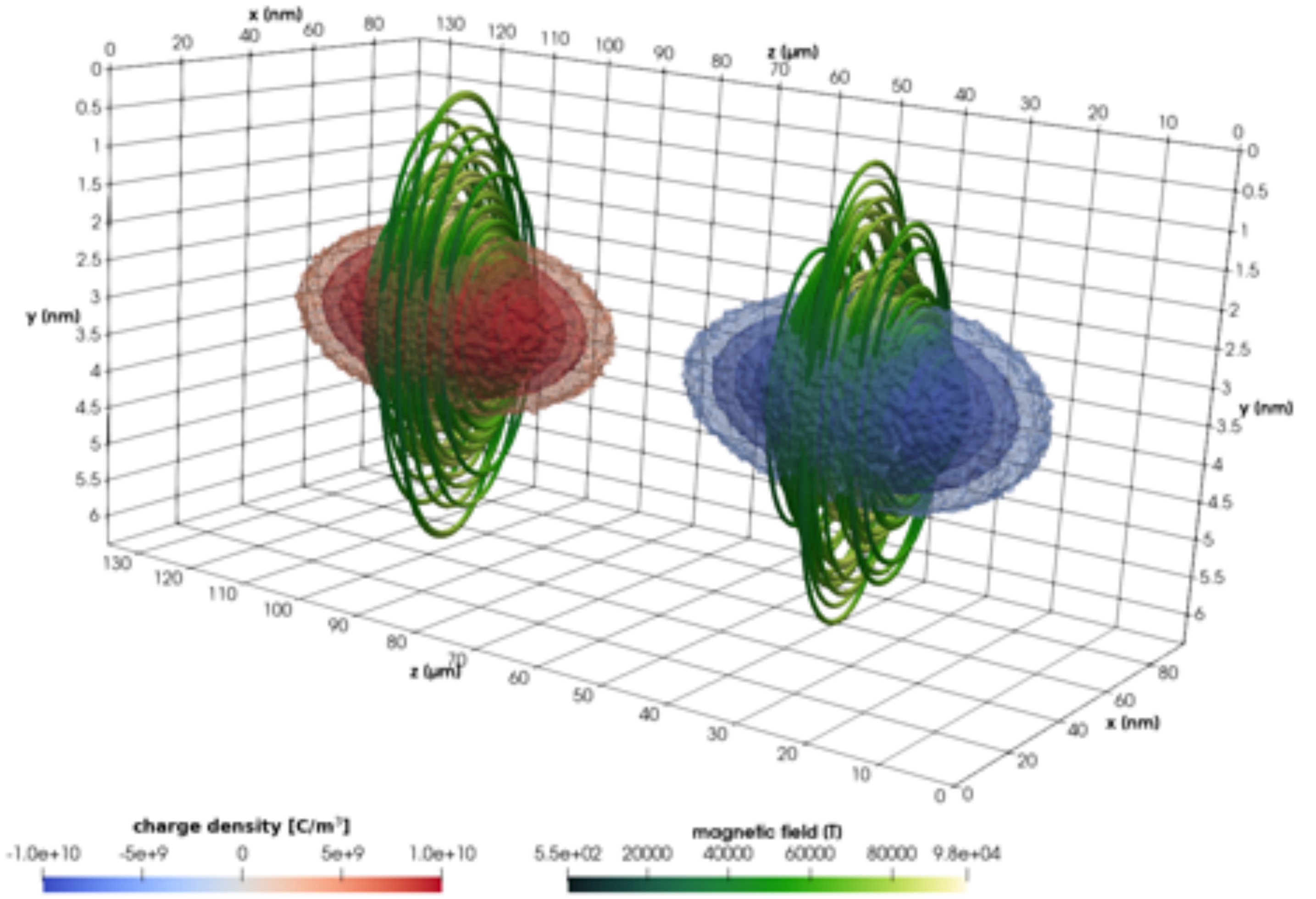


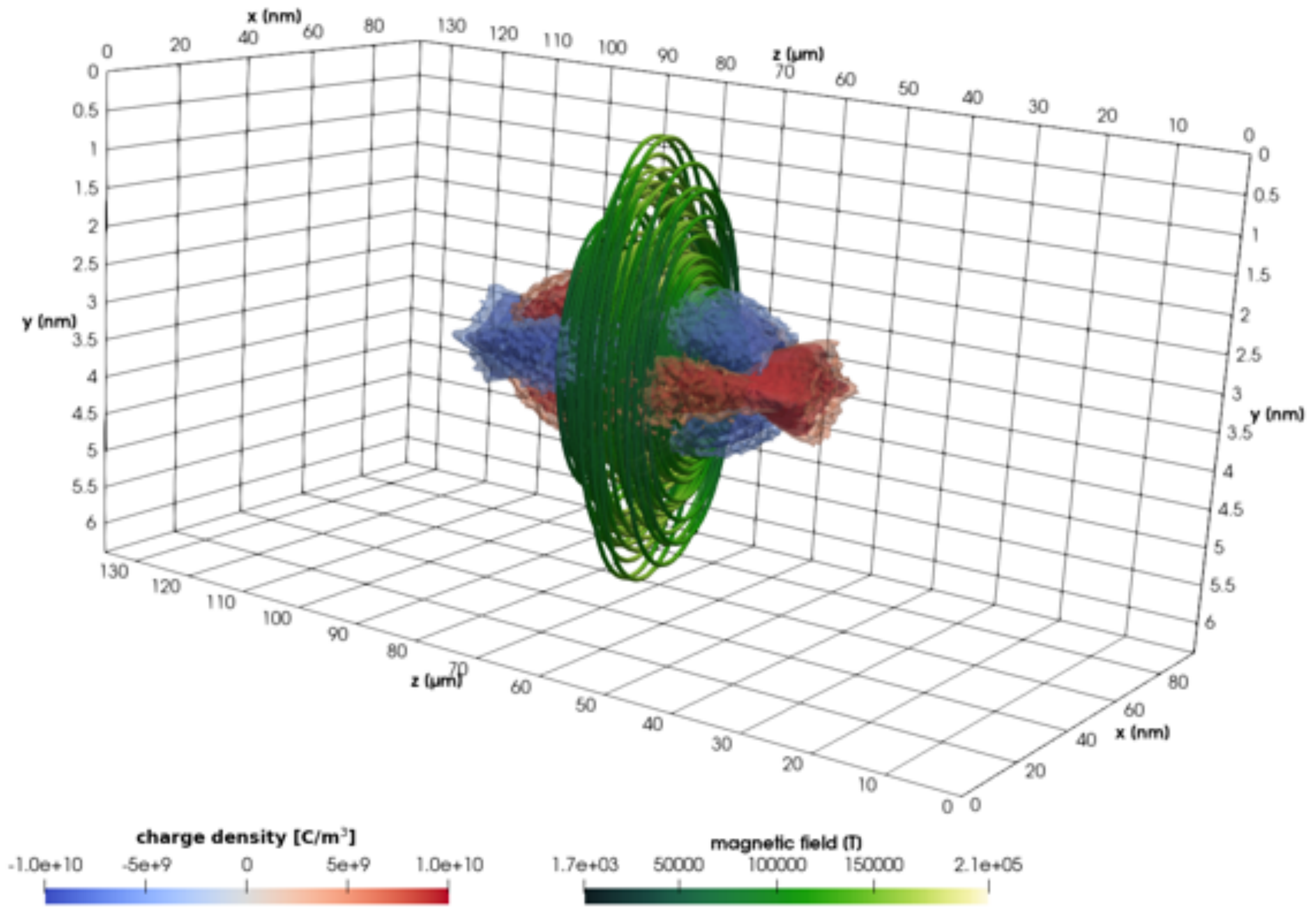
Y. Zhao *et al.*,
PoP 27, 113105 (2020)

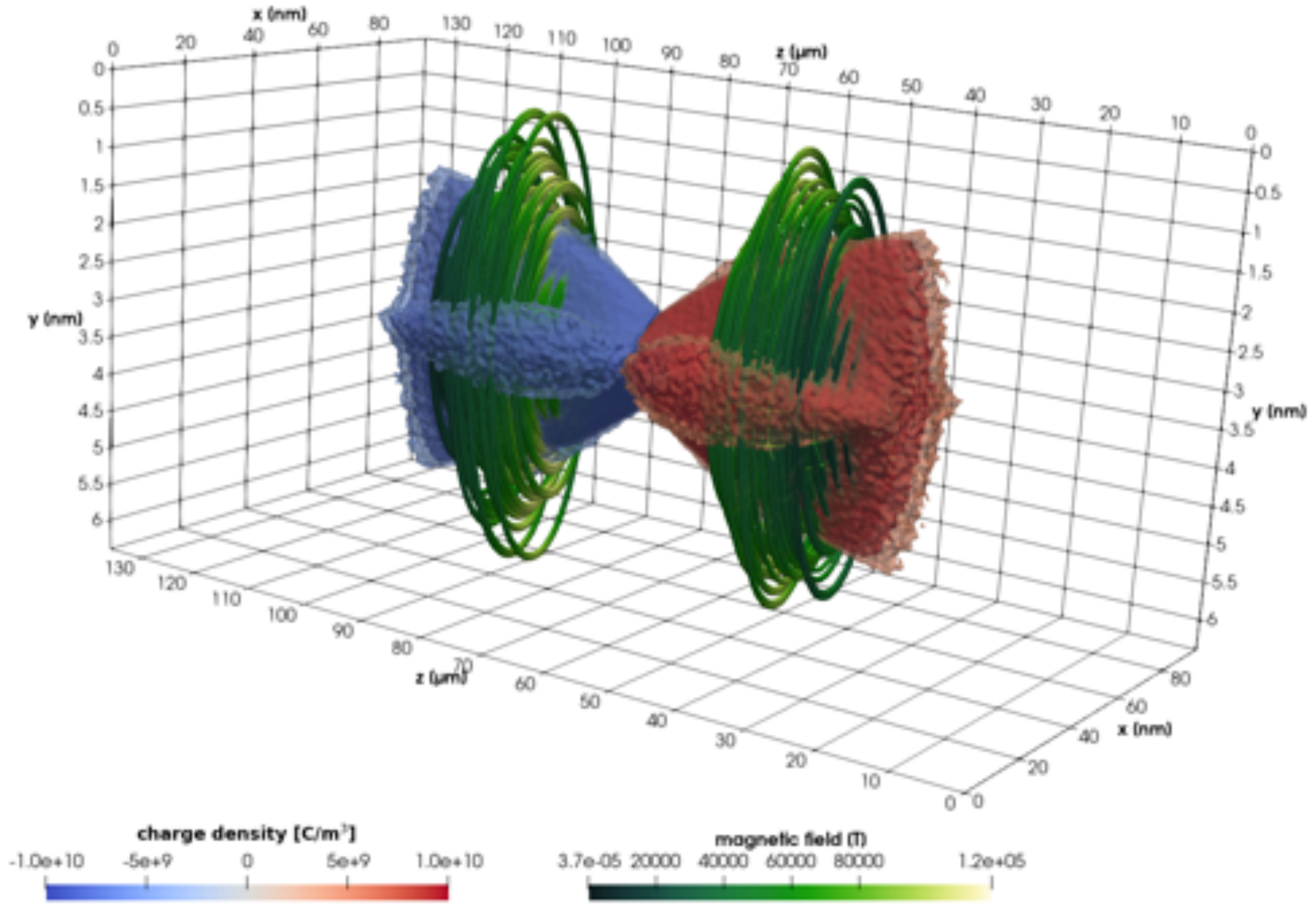
C.B. Schroeder *et al.*,
JINST 17, P05011 (2022)

Verification of beam-beam IP codes

- **Beam disruption:** beams change shape as they collide
- **Beamstrahlung:** particles emit hard photons and lose energy
- **Secondary e^+/e^- pair creation:** can affect the beam evolution



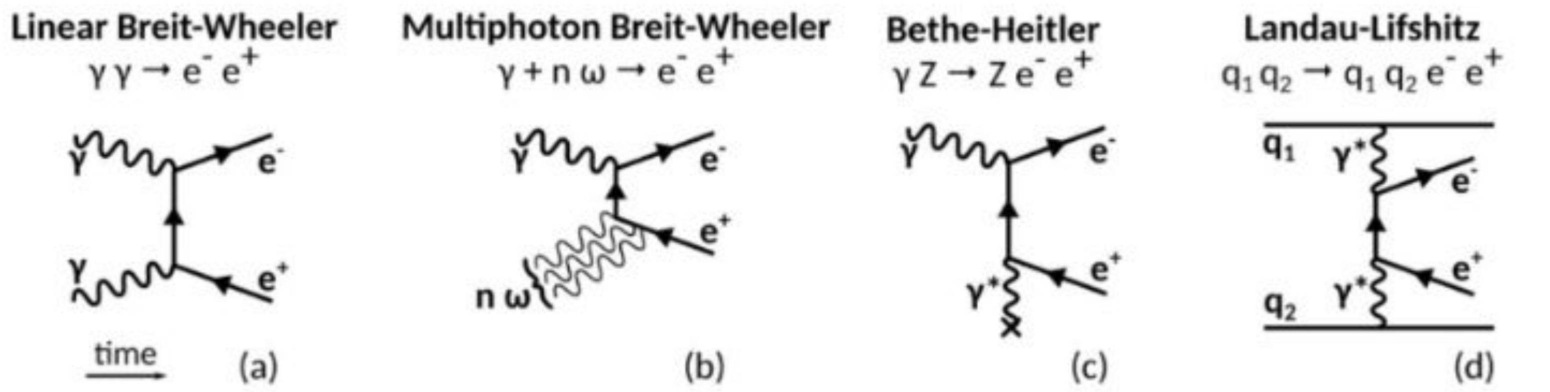




Current simulation tools represent QED processes (photon & e^+/e^- pair creation) as combination of

- **Coherent processes:** particle creation in high field (e.g. Breit-Wheeler), under the local constant field approximation (LCFA)
- **Incoherent processes:** particle creation in collisions between individual particles (e.g. Bethe-Heitler)

Unclear whether these approximations/models are still valid for 10 TeV
→ experimental nonlinear QED benchmarking needed



EuPRAXIA with its combination of GeV electrons and high-intensity laser an interesting testbed!

Which field strength in beam frame compared to Schwinger can be reached?

Conclusion

Plasma accelerator technology is of high interest for the future of particle physics

- Reduce the size of future colliders (reduced construction cost, environmental impact)
- Potential for reduced operation cost (higher luminosity/power)
- Upgrade path for Higgs-factory LCs (repurposing of ILC/CLIC/C^3 infrastructure - LCVision)

EuPRAXIA, as a flagship facility and with its application focus, can lead the way toward more mature plasma accelerators → credibility for complex applications

EuPRAXIA is well positioned to contribute to

- Technology R&D and provide critical experimental facilities
  - LPA demonstrator stages (at low average power, approaching collider emittances)
  - PWFA staging
  - Positron beam test capabilities
- Enable physics verification and simulation code benchmarking
  - Experimental flat beam tests
  - Experimental hosing mitigation tests
  - Experimental nonlinear QED tests