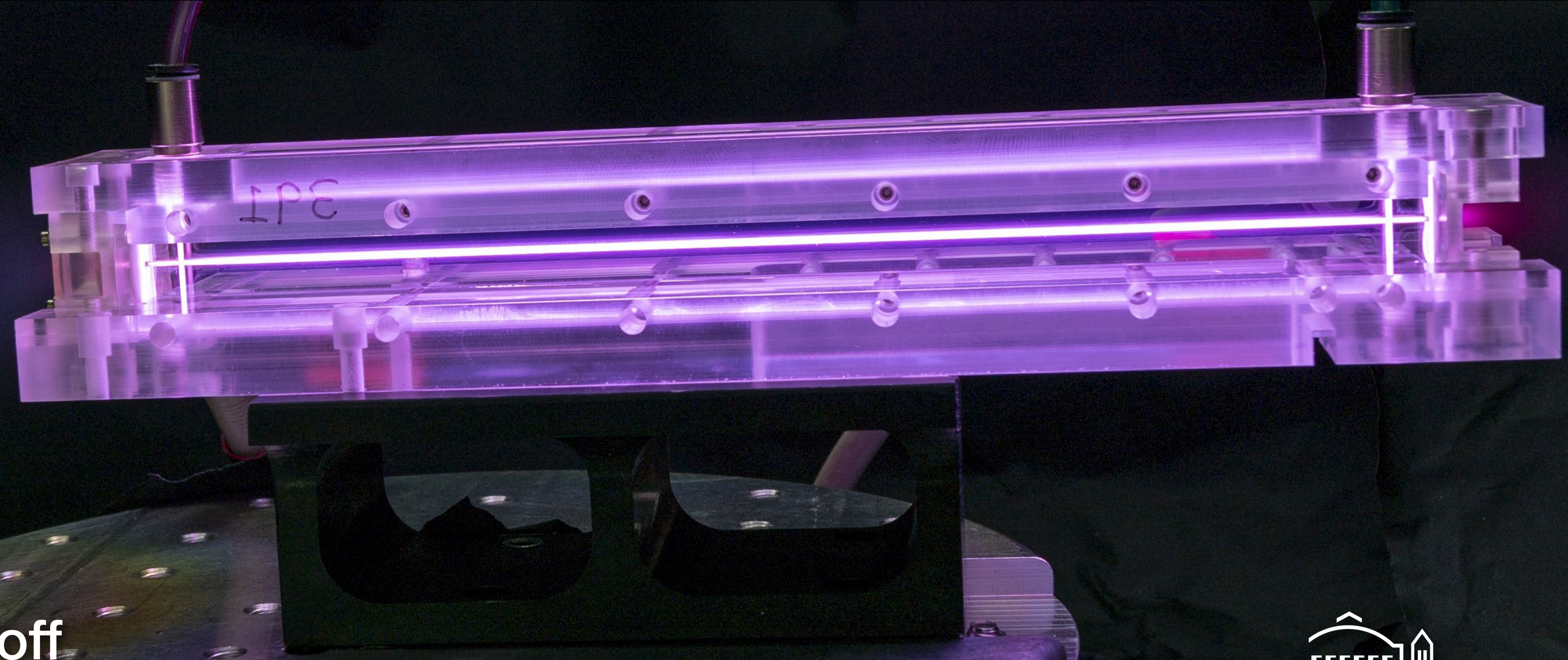
Plasma accelerator activities (laser + beam)

US and European perspectives



Jens Osterhoff

Lawrence Berkeley National Laboratory

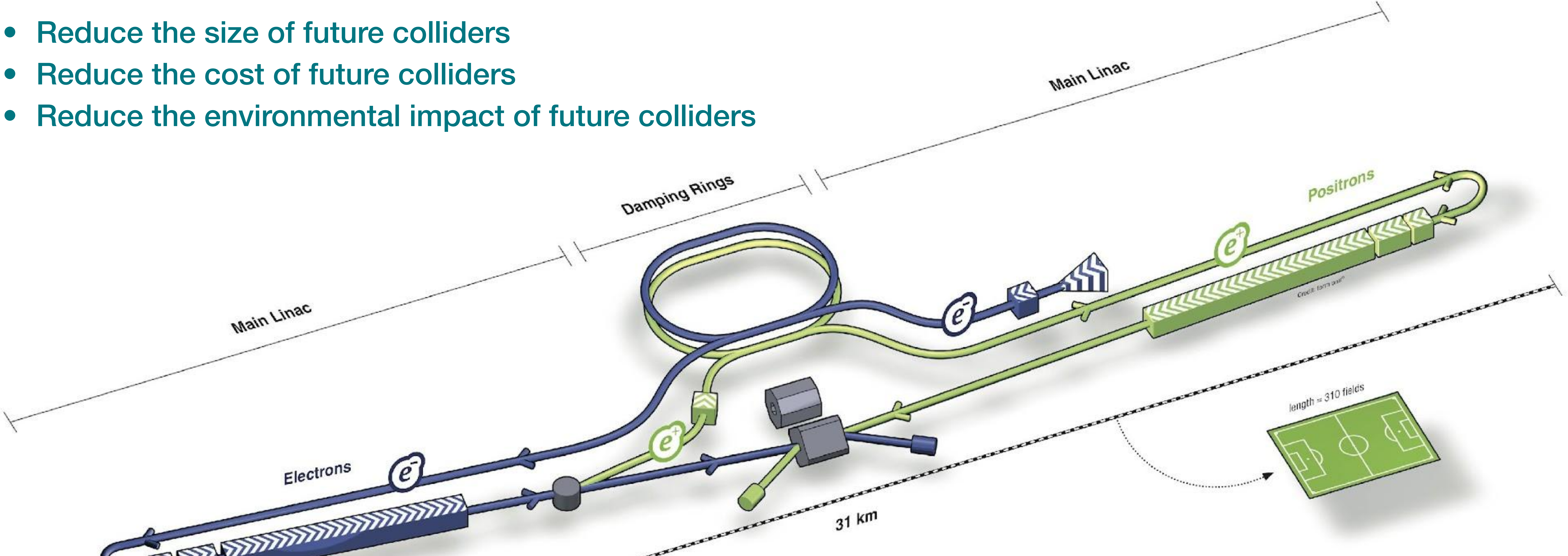
June 7th, 2024
LDG Meeting, BNL

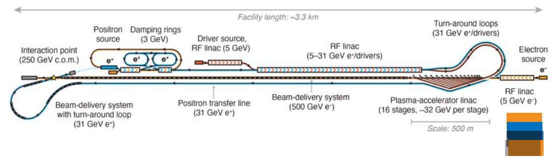
BERKELEY LAB
Bringing Science Solutions to the World

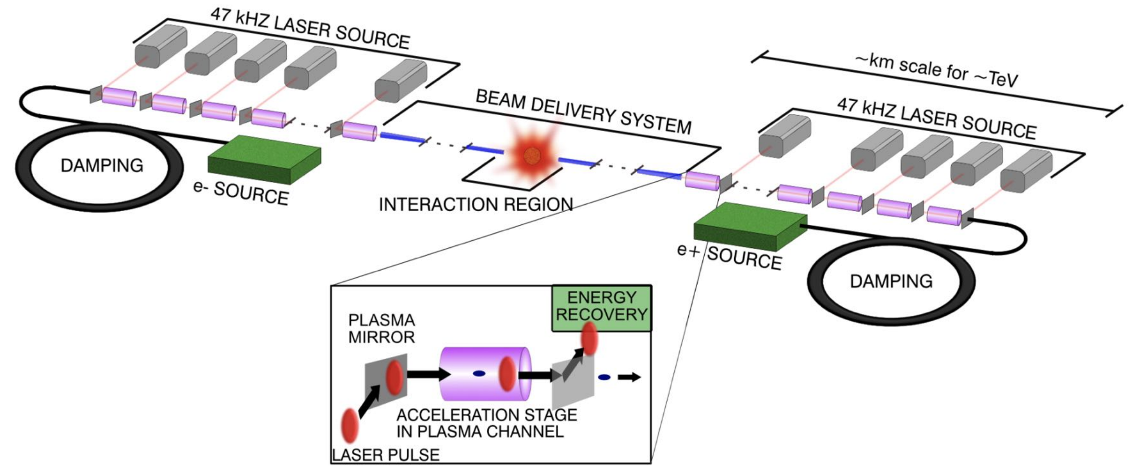
Work supported by the U.S. DOE, Office of Science, Office of High Energy Physics, under Contract No. DE-AC02-05CH11231

Advanced accelerator (> 1 GV/m) goals for particle physics

- Reduce the size of future colliders
- Reduce the cost of future colliders
- Reduce the environmental impact of future colliders







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*

*for the linac, not including BDS

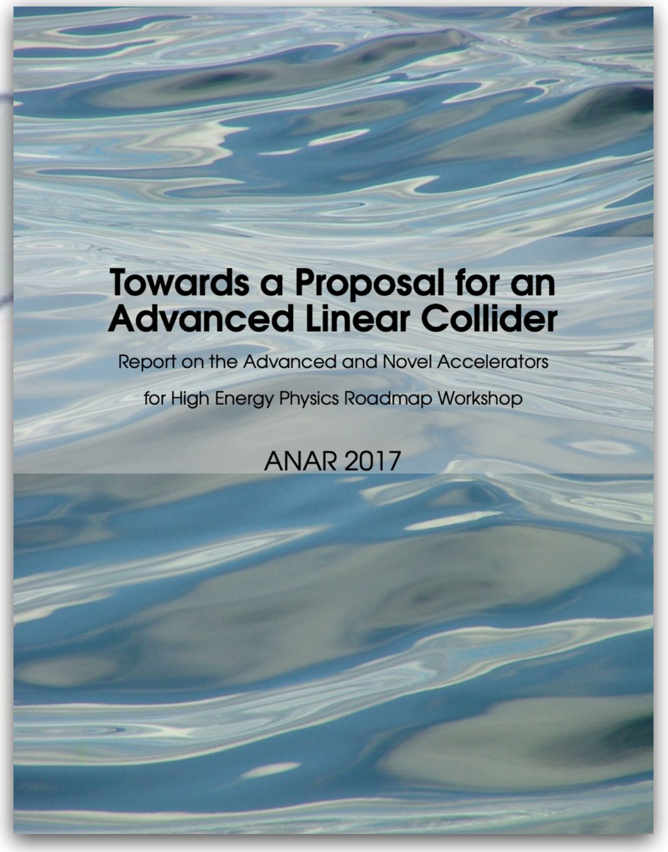
C.B. Schroeder *et al.*, **JINST** 18 T06001 (2023)

Advanced accelerator research is a global enterprise

ALEGRO

Advanced LinEar collider study GROup

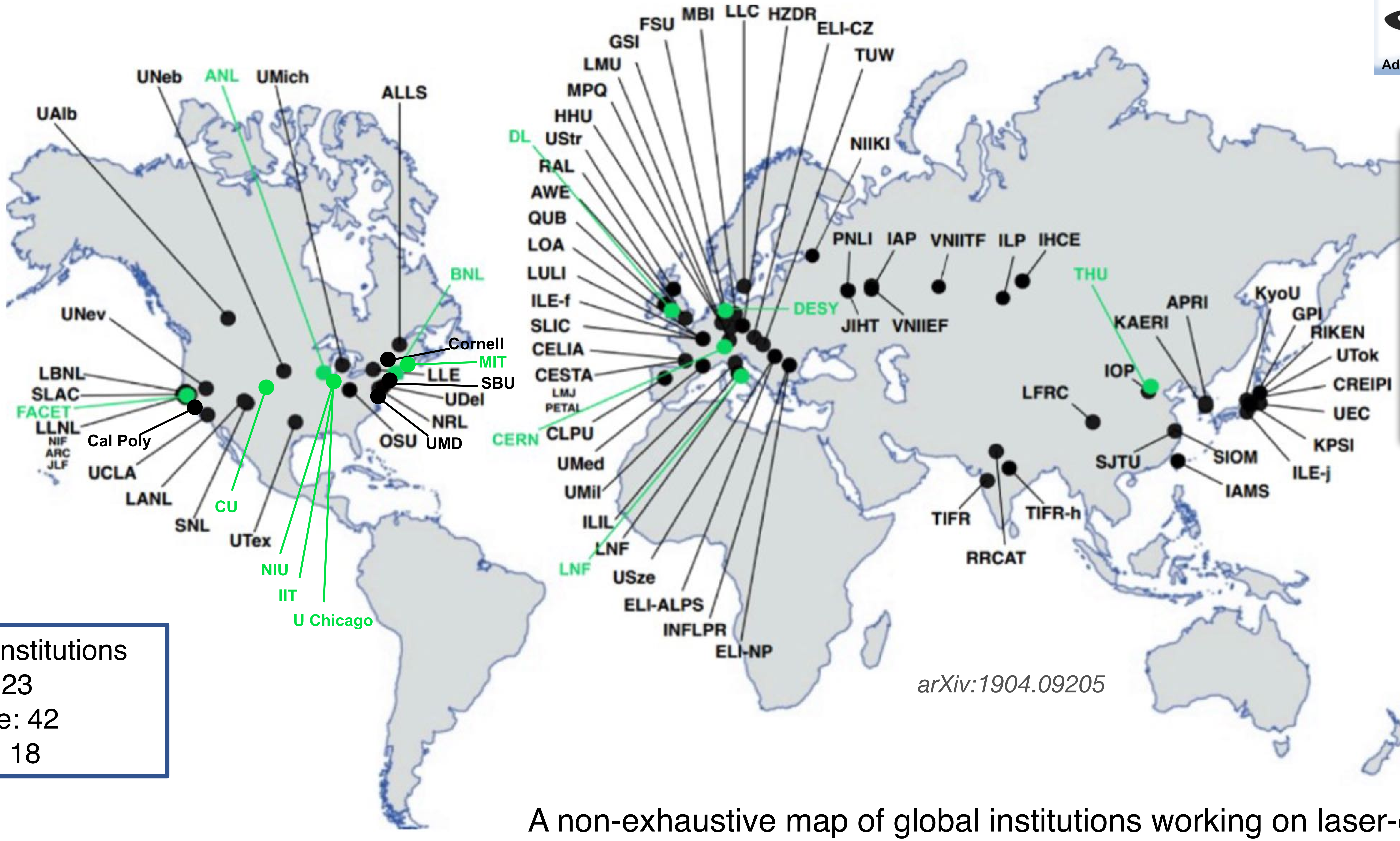
founded in 2017



Towards a Proposal for an Advanced Linear Collider

Report on the Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop

ANAR 2017



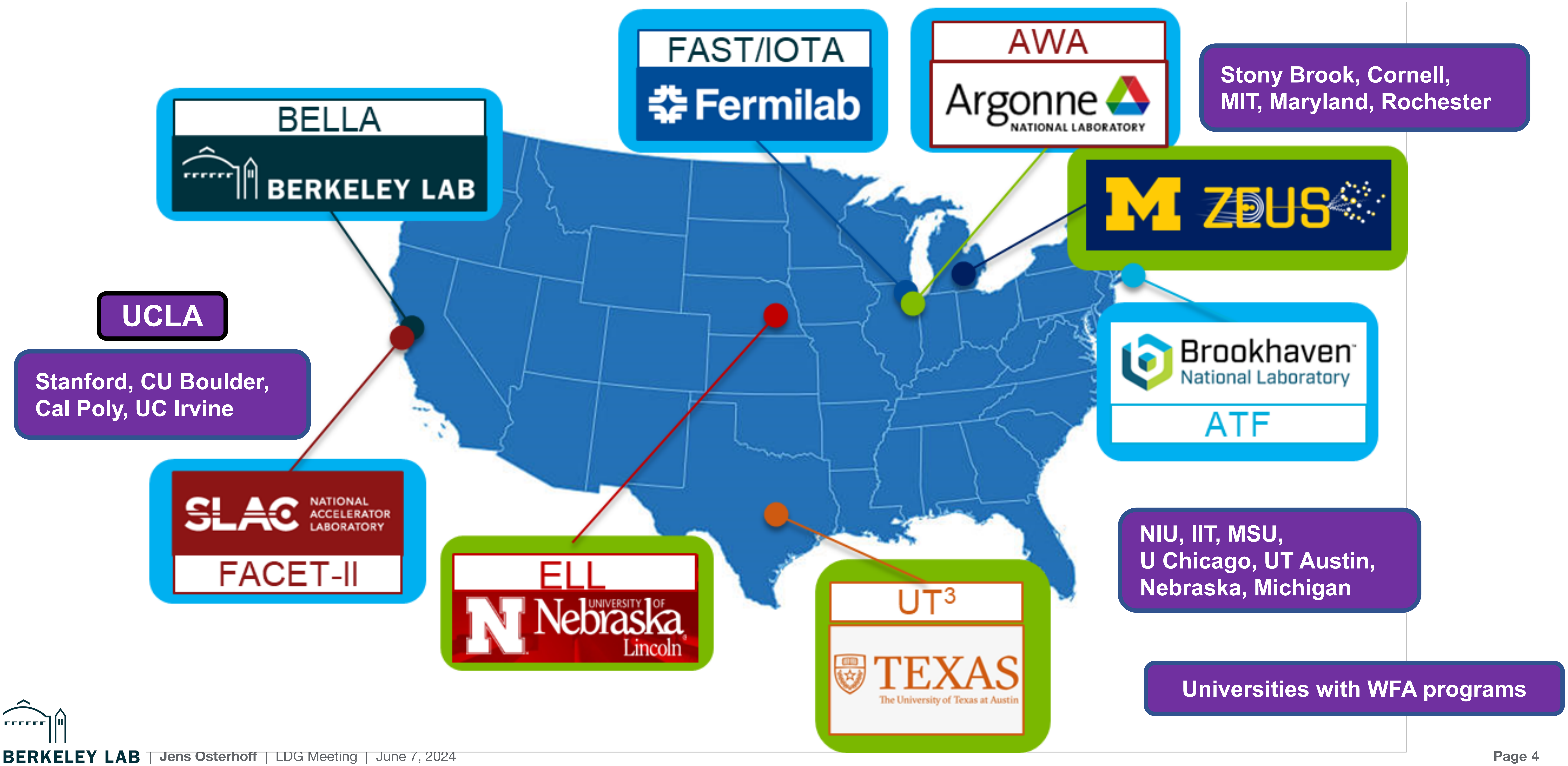
arXiv:1904.09205

Number of Institutions
US: 23
Europe: 42
Asia: 18

A non-exhaustive map of global institutions working on laser-driven plasma acceleration (**black**) and beam-driven plasma/structure acceleration (**green**).

Advanced accelerator research in the US

Large Beam Test Facilities
Universities
National Labs



BELLA
BERKELEY LAB

FAST/IOTA
Fermilab

AWA
Argonne NATIONAL LABORATORY

Stony Brook, Cornell, MIT, Maryland, Rochester

ZEUS

UCLA

Stanford, CU Boulder, Cal Poly, UC Irvine

Brookhaven National Laboratory
ATF

SLAC NATIONAL ACCELERATOR LABORATORY
FACET-II

ELL
UNIVERSITY OF Nebraska Lincoln

UT^3
TEXAS
The University of Texas at Austin

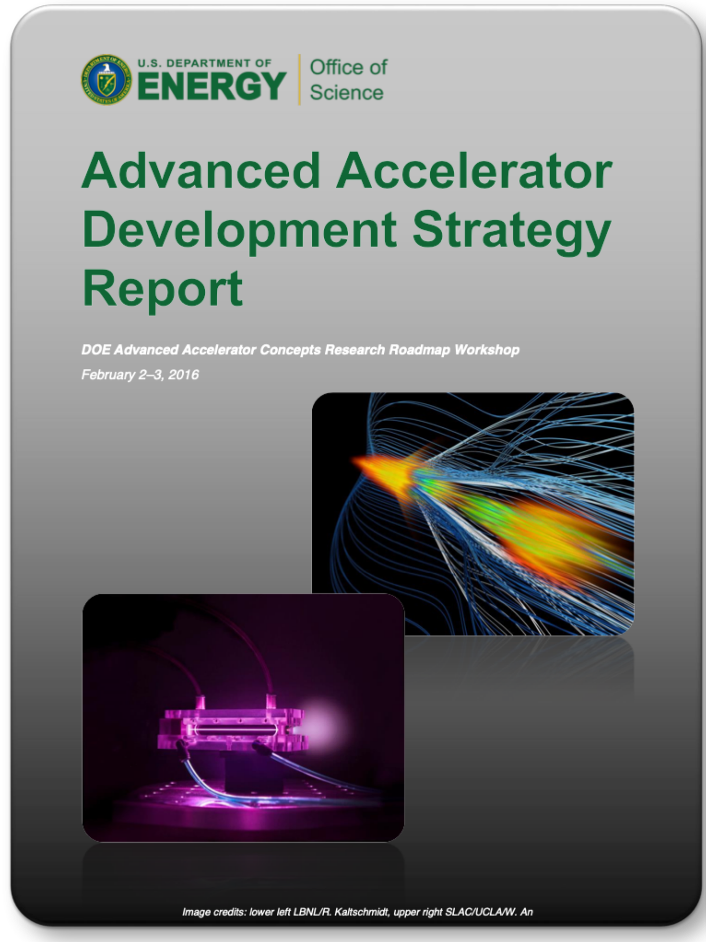
NIU, IIT, MSU, U Chicago, UT Austin, Nebraska, Michigan

Universities with WFA programs

2016 DOE AAC R&D Roadmap and 2023 P5 Report set path for wakefield technology R&D toward a future collider

DOE AAC Roadmap (2016)

developed from 2014 P5 Report and 2015 HEPAP Subcommittee recommendations

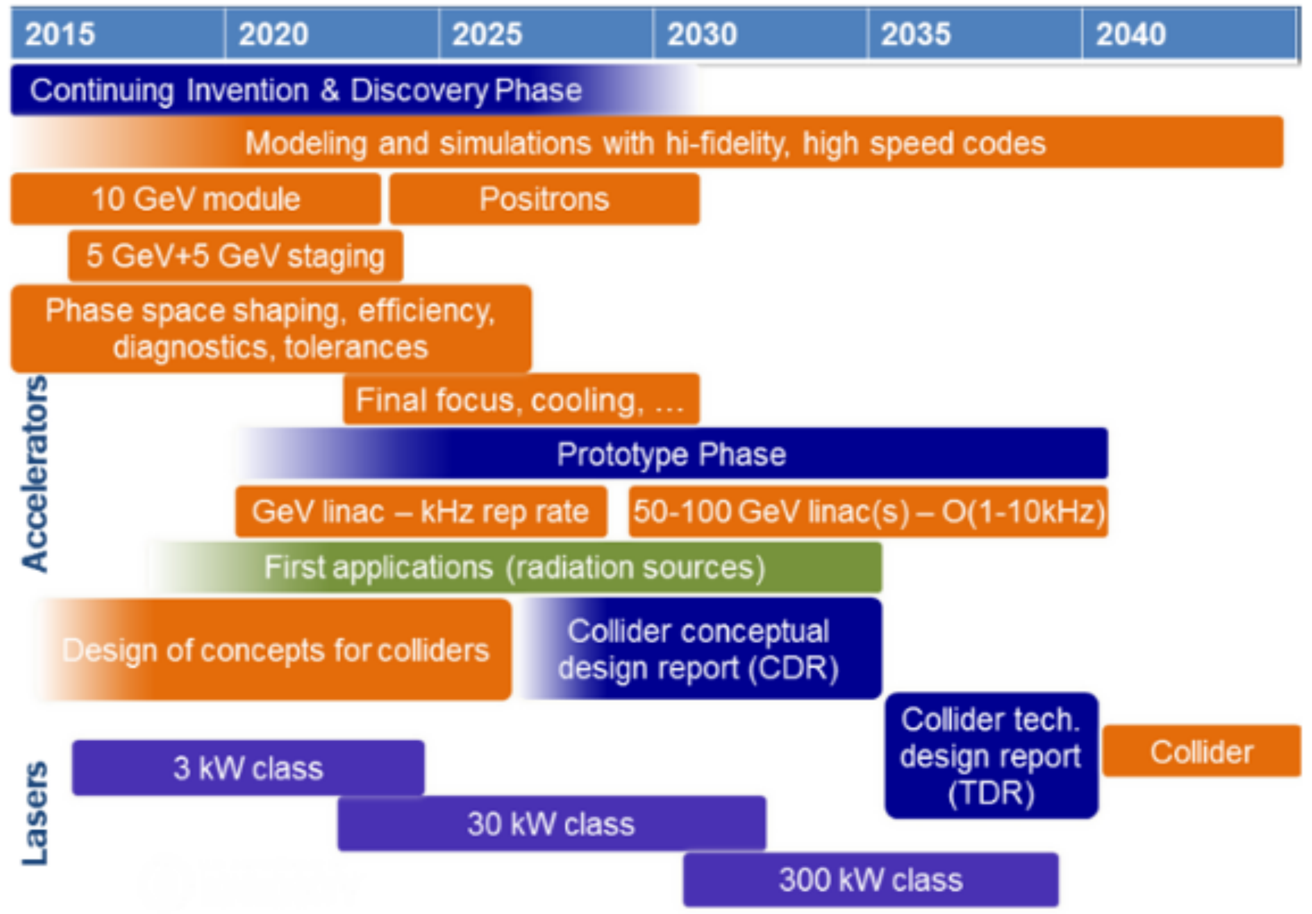

U.S. DEPARTMENT OF ENERGY | Office of Science

Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop

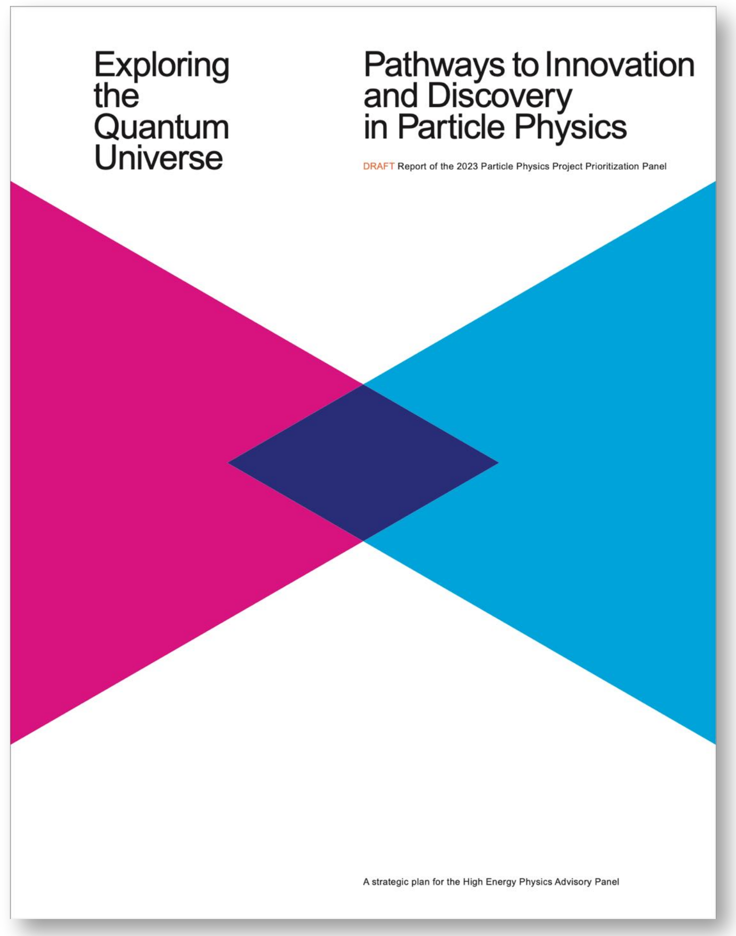
February 2–3, 2016

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An



- HEP application main driver of US R&D
- DOE AAC Roadmap defined path toward a future particle physics machine
- Identified key technology R&D steps
- Guided US AAC R&D over past 8 years
- Roadmap of unconstrained scenario

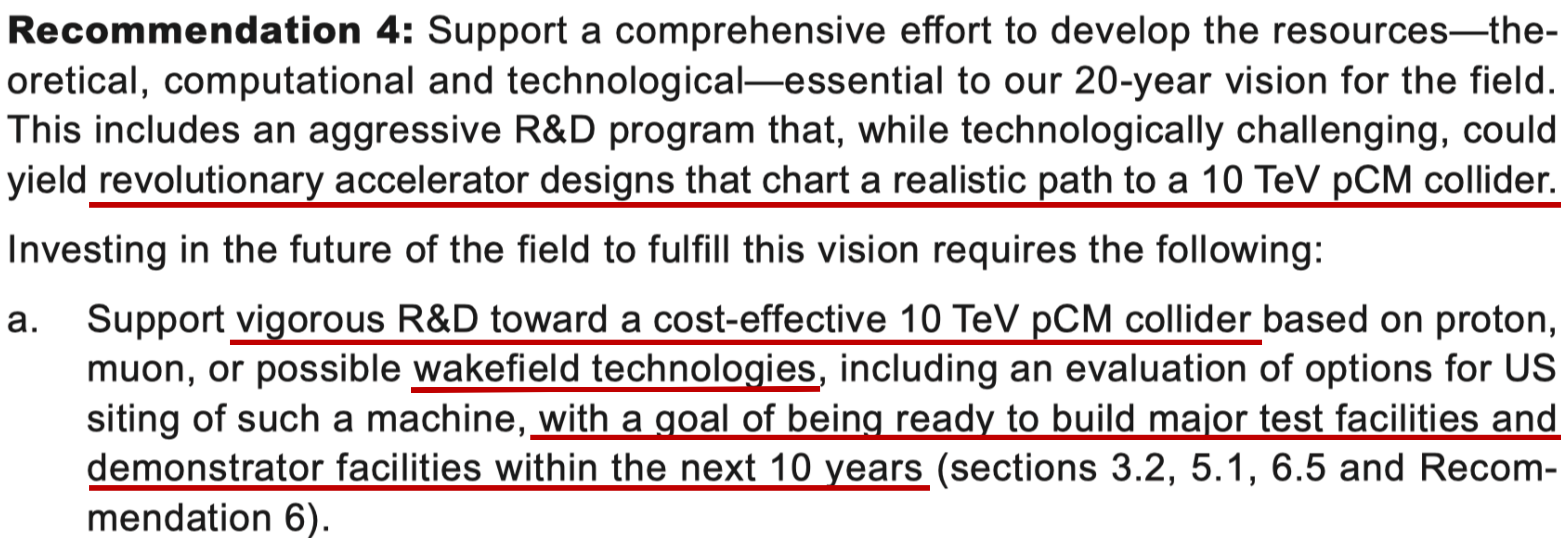
P5 Report (2023)


Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

DRAFT Report of the 2023 Particle Physics Project Prioritization Panel

A strategic plan for the High Energy Physics Advisory Panel


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.

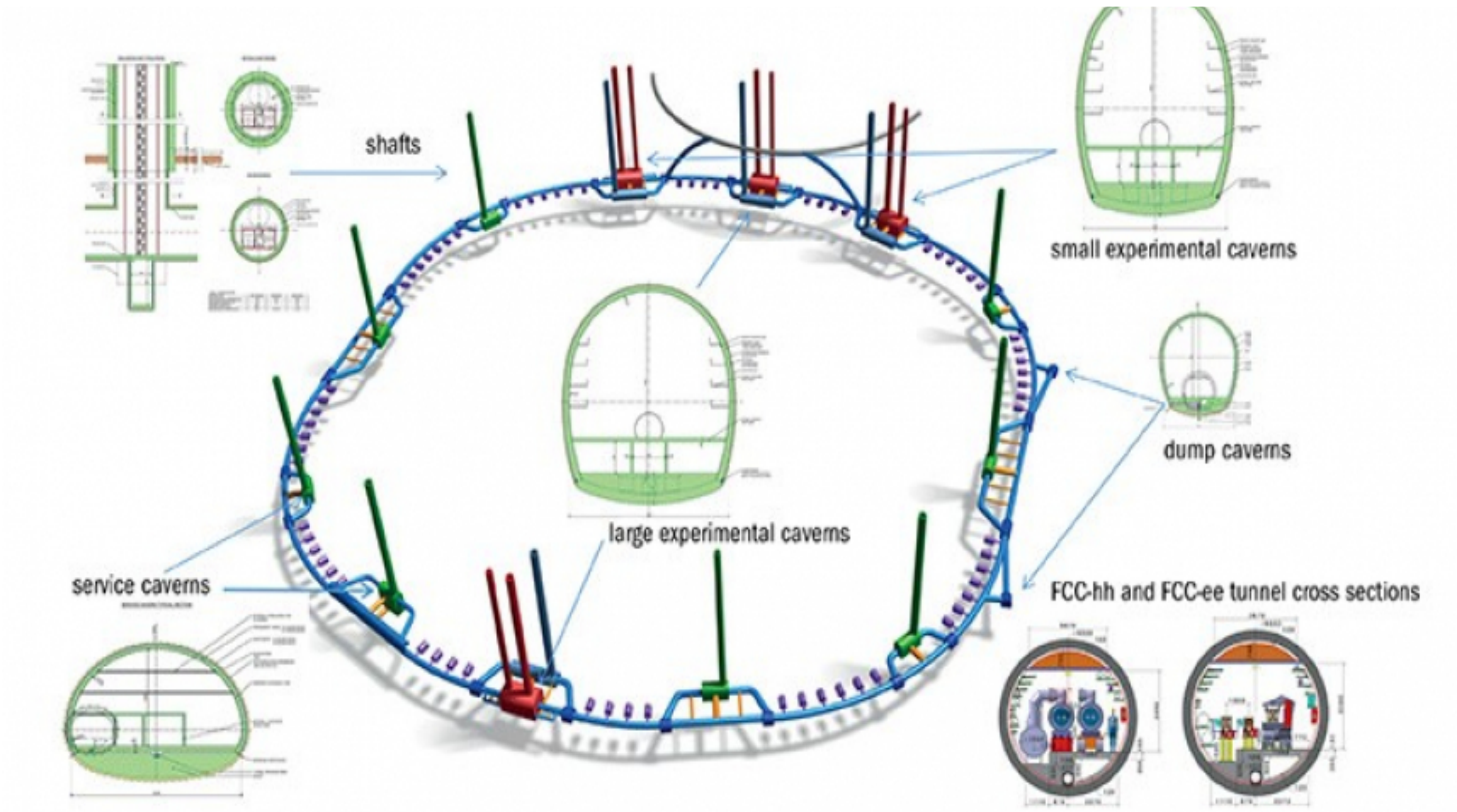
Investing in the future of the field to fulfill this vision requires the following:

a. Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years (sections 3.2, 5.1, 6.5 and Recommendation 6).

10 TeV pCM technology must be developed, no concept ready, need for test facilities established

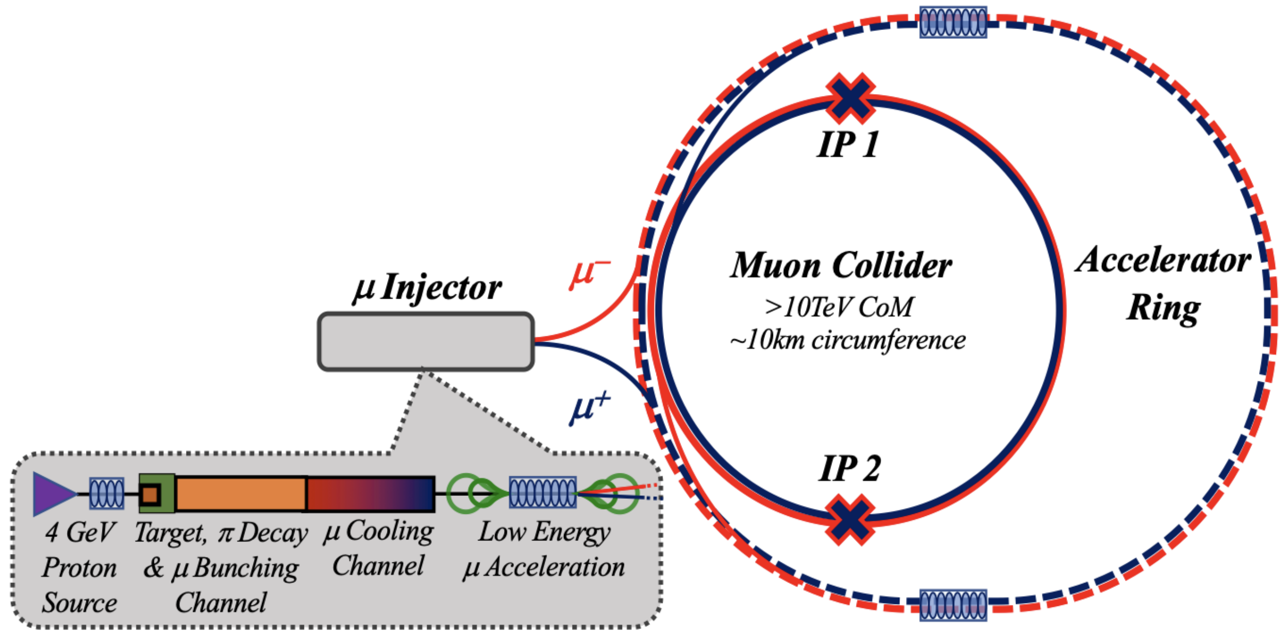
Proton collider

Key needs: high field magnets, detectors



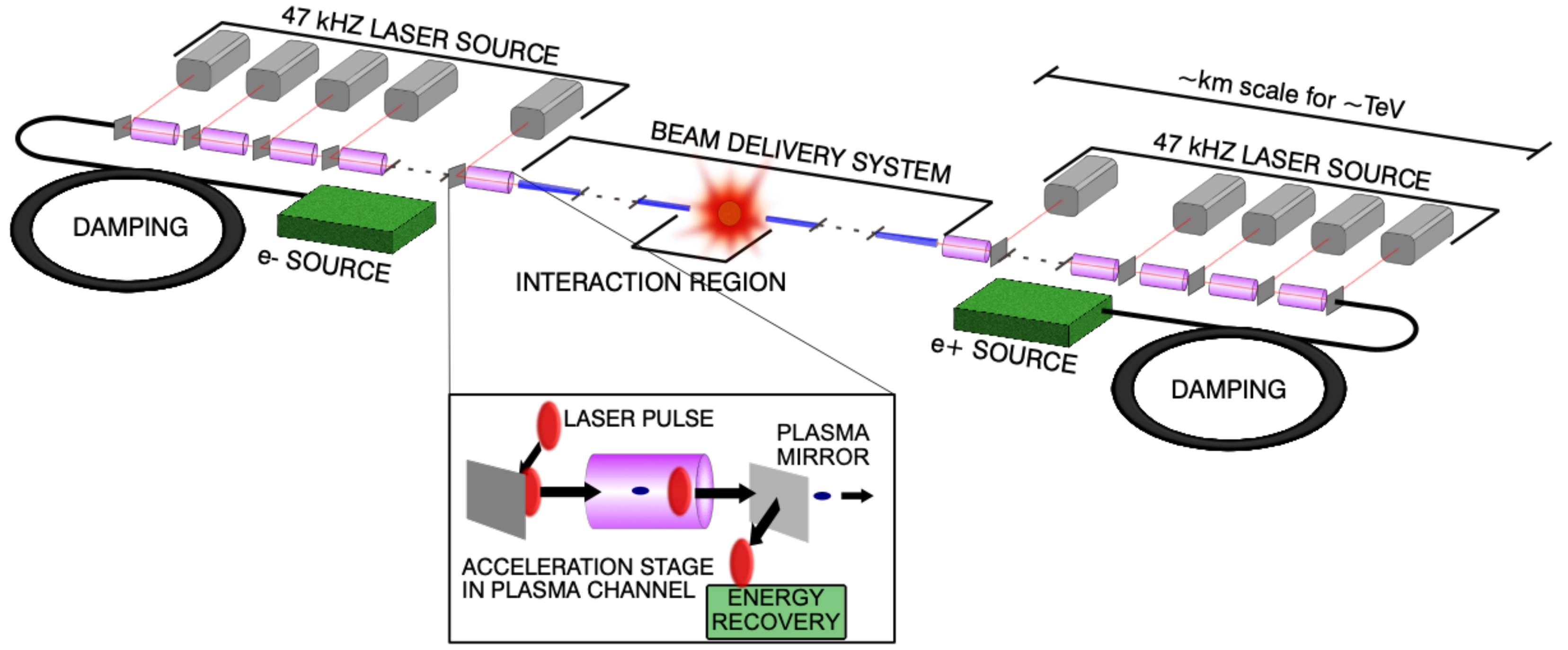
Muon collider

Key needs: targets, cooling



Linear wakefield lepton collider

Key needs: avg. power, efficiency, precision *(kBELLA)* positrons *(FACET-II)*, transformer ratio *(AWA)*



> ***“All options for a 10 TeV pCM collider are new technologies under development and R&D is required before we can embark on building a new collider”***
>
> *P5 Report (2023), p. 17*

Challenges for all concepts: size, luminosity, power, detector

e^+e^- collisions offer similar physics to muons

- Potential advantage: relatively clean detector environment
- Conventionally too large and power hungry beyond few TeV — Advanced accelerators (> 1 GV/m) may solve this challenge

Conceptual physics considerations determine parameter ranges

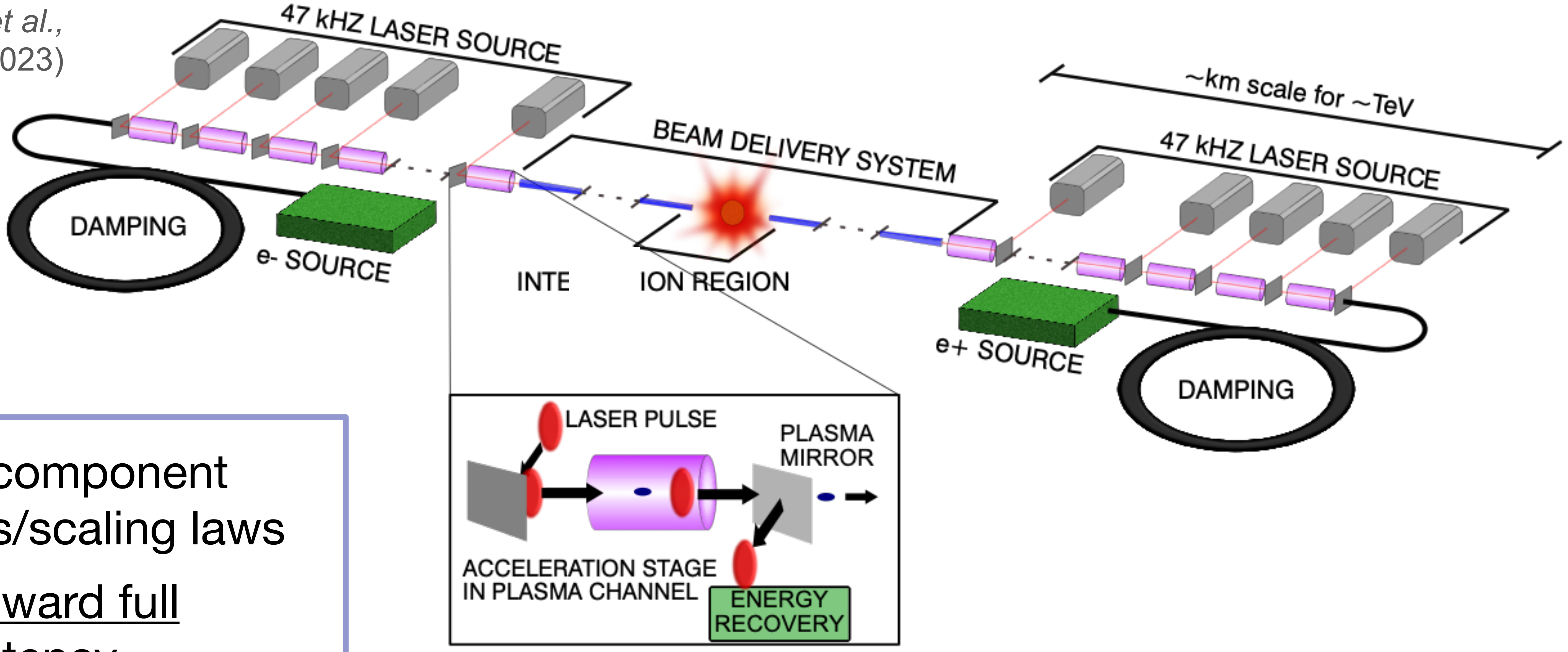
Basic design choices driven by system optimization

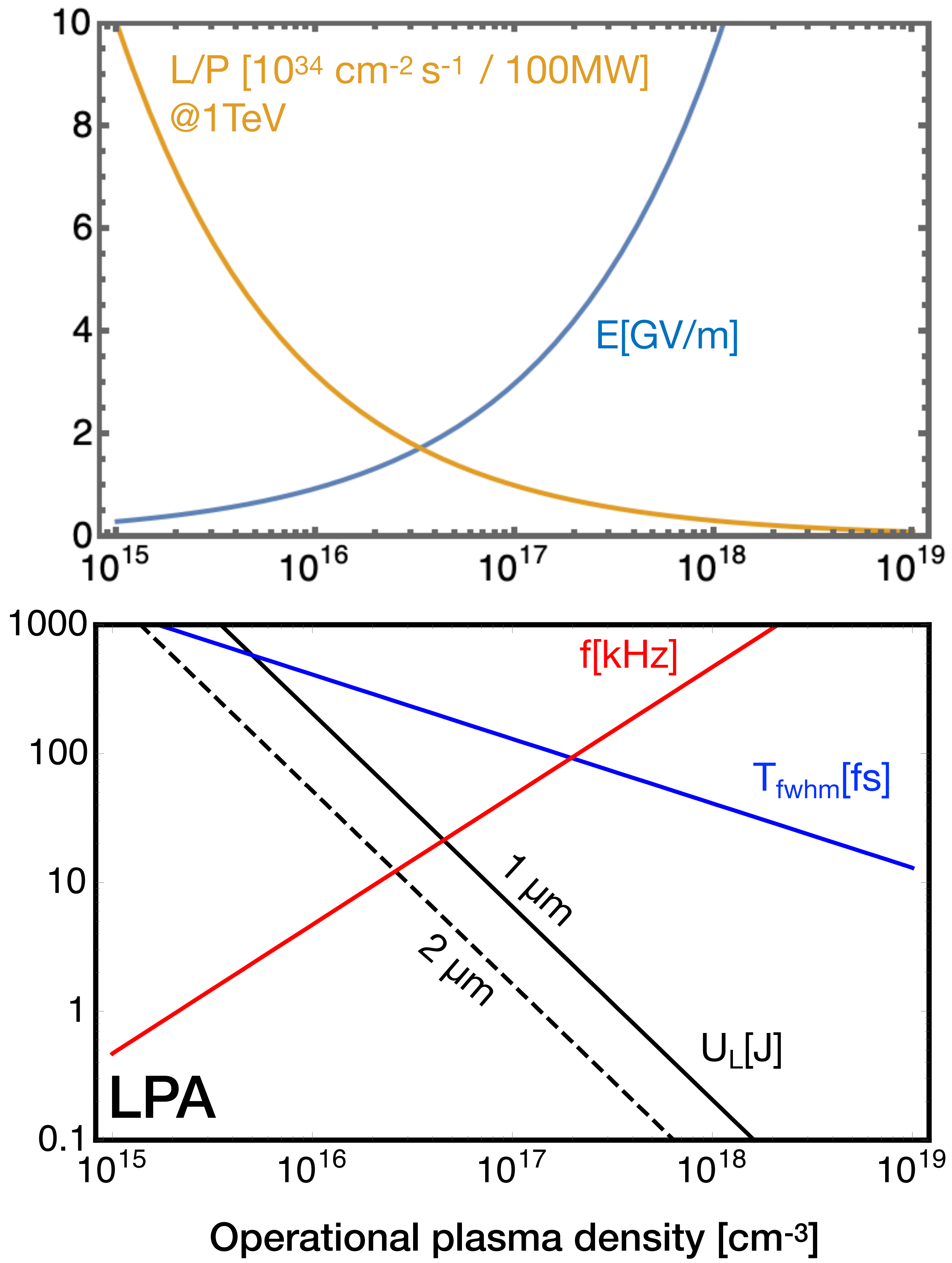
- Minimizing linac length (gradient > GV/m)
- Maximizing energy efficiency (luminosity/power)

} Restricts plasma density range, energy gain per stage → staging

- Plasma density sets bunch charge (also limited by Beamstrahlung), luminosity requires repetition rate

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)

New US initiative to organize the community for an end-to-end 10 TeV pCM wakefield collider design

> *“Wakefield concepts for a collider are in the early stages of development. A critical next step is the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout.”*
>
> ***P5 Report (2023), p. 85***

- *Goal*: **end-to-end design concept** including sub-systems (detectors, beam delivery), cost estimates, **self-consistency**, **based on strong physics case**
- LBNL, SLAC, ANL launched 10 TeV wakefield collider initiative
    - Organizes the **US wakefield accelerator community** *(biweekly meetings; since January)*
    - Strong **links to worldwide activities** emerging through ICFA ANA ALEGRO and HALHF
    - Strong **links to particle physics incl. detectors** *(monthly meetings at LBNL, and with SLAC; since April)*

New US initiative to organize the community for an end-to-end 10 TeV pCM wakefield collider design

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> ***P5 Report (2023), p. 85***

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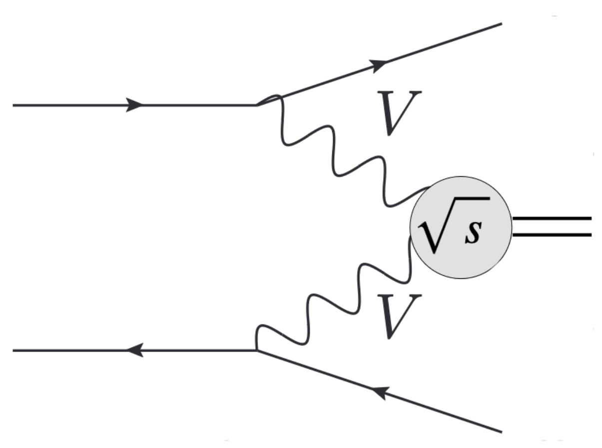
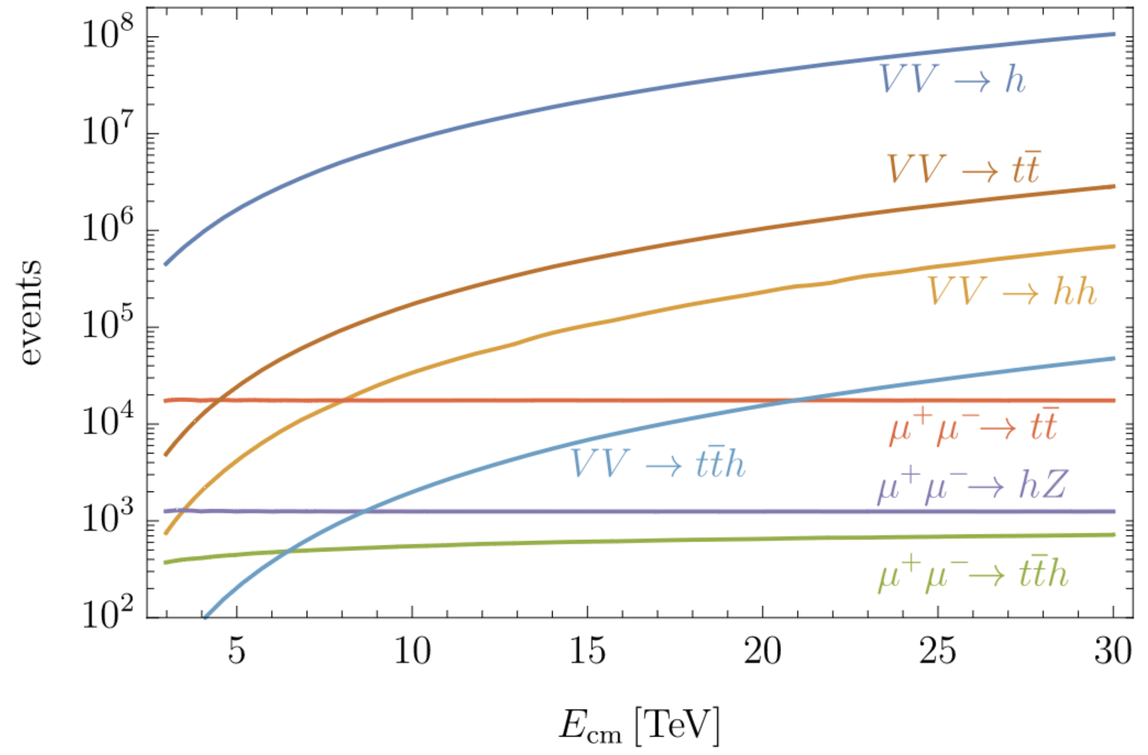
First: engage particle physics community



Muon Collider Physics Summary https://arxiv.org/abs/2203.07256

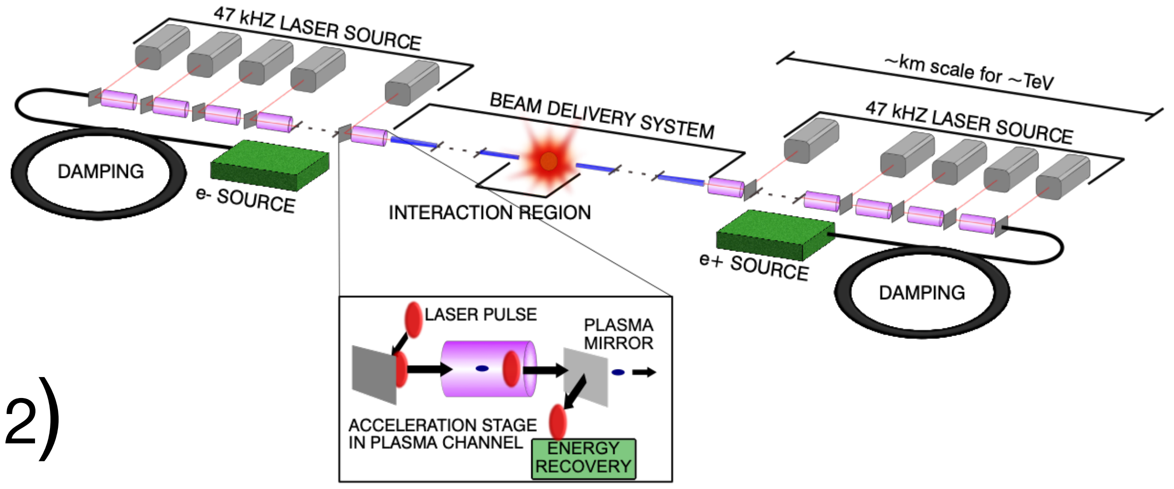


- **Cannot feed off pre-existing physics case (unlike for a Higgs Factory)**
- At 10 TeV, Vector Boson Fusion will dominate annihilation of pairs
- e^+/e^- or e^-/e^- or γ/γ collider?
- Balance technical readiness and achievable lumi vs. physics demands
- *More:* expect strong Beamstrahlung at IP, revisit paradigms - round vs. flat beams → detector design

The advanced accelerator community is retiring key risks for a plasma wakefield linac at high rate

Beam dynamics risks retired

- Hosing **instability surpression** → Mehrling *et al.*, **PRL** 121 (2018); Benedetti *et al.*, **Phys. Plasmas** 28 (2021)
- **Beam scattering** in plasma **mitigated** by strong focussing → Zhao *et al.*, **Phys. Plasmas** 27 (2020)
- **Synchrotron radiation effects mitigated** by needed emittances → Schroeder *et al.*, **JINST** 17 (2022)



Rapid, groundbreaking experimental community progress

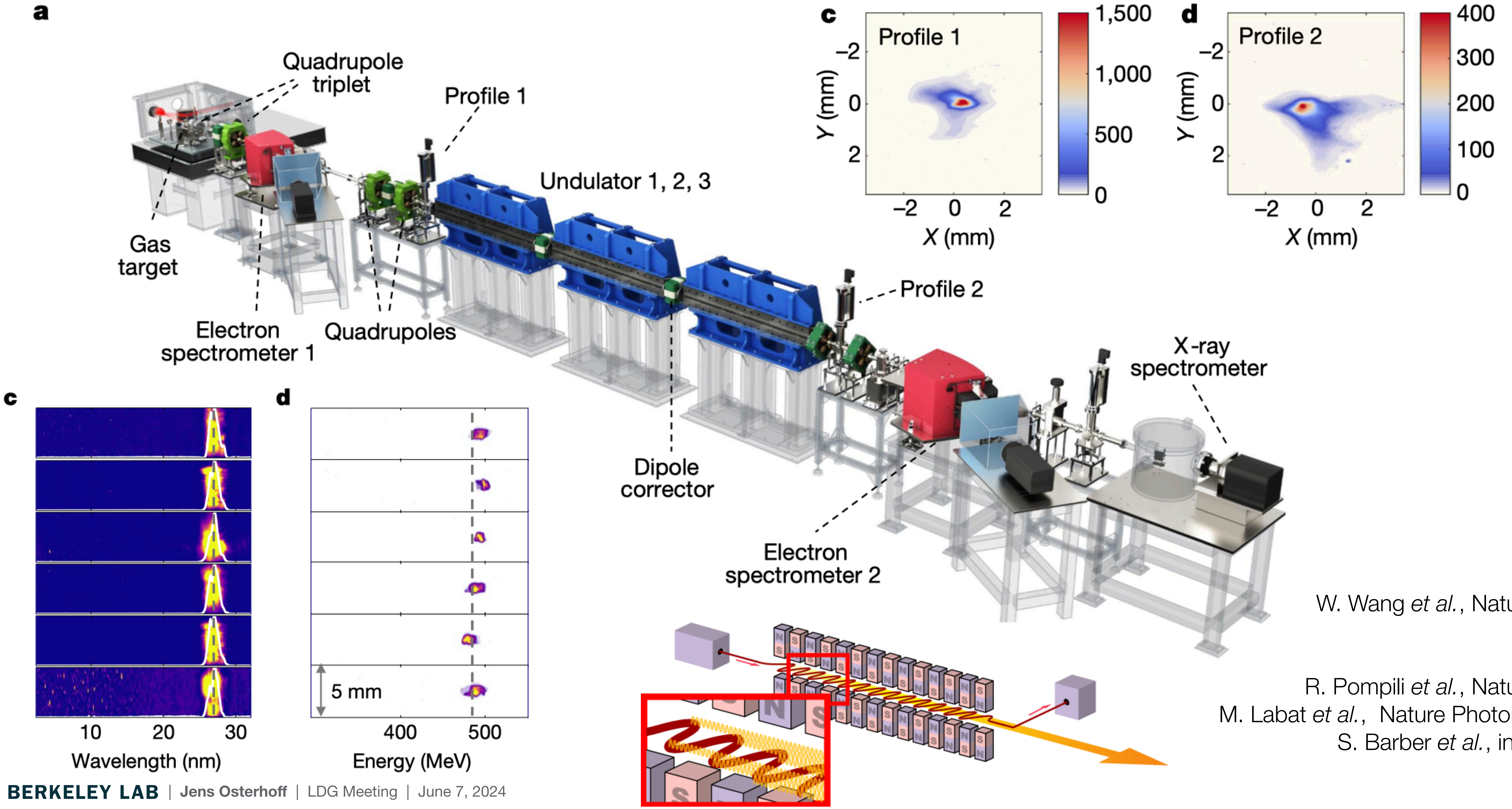
- **Staging** of plasma modules → Steinke *et al.*, **Nature** 530 (2016), **GeV-level staging** experiments to start in 2024
- **Stability and control** of plasma stages → Maier *et al.*, **PRX** 10 (2020)
- **Sources and bright beam generation** → Deng *et al.*, **Nature Physics** 15 (2019)
- **High repetition rates** in plasmas → D'Arcy *et al.*, **Nature** 603 (2022)
- **Beam-quality preservation and efficiency** by bunch shaping → Lindstrøm *et al.*, **PRL** 126 (2021), Lindstrøm *et al.*, arXiv:2403.17855 (2024)

Additional technical challenges require R&D and test facilities

- **10's to 100's of stages:** beam matching / coupling between including efficiency ≥ 99%
- Small accelerating structures place challenging **alignment and jitter tolerances**
- **Wall-plug power (operating costs) limits of energy reach** for advanced accelerators
- **Compact delivery system and final focus, spin transport in plasmas, positron acceleration**

Laser plasma accelerator drives an FEL at 27 nm

State-of-the-art in compact accelerators is FEL beam quality

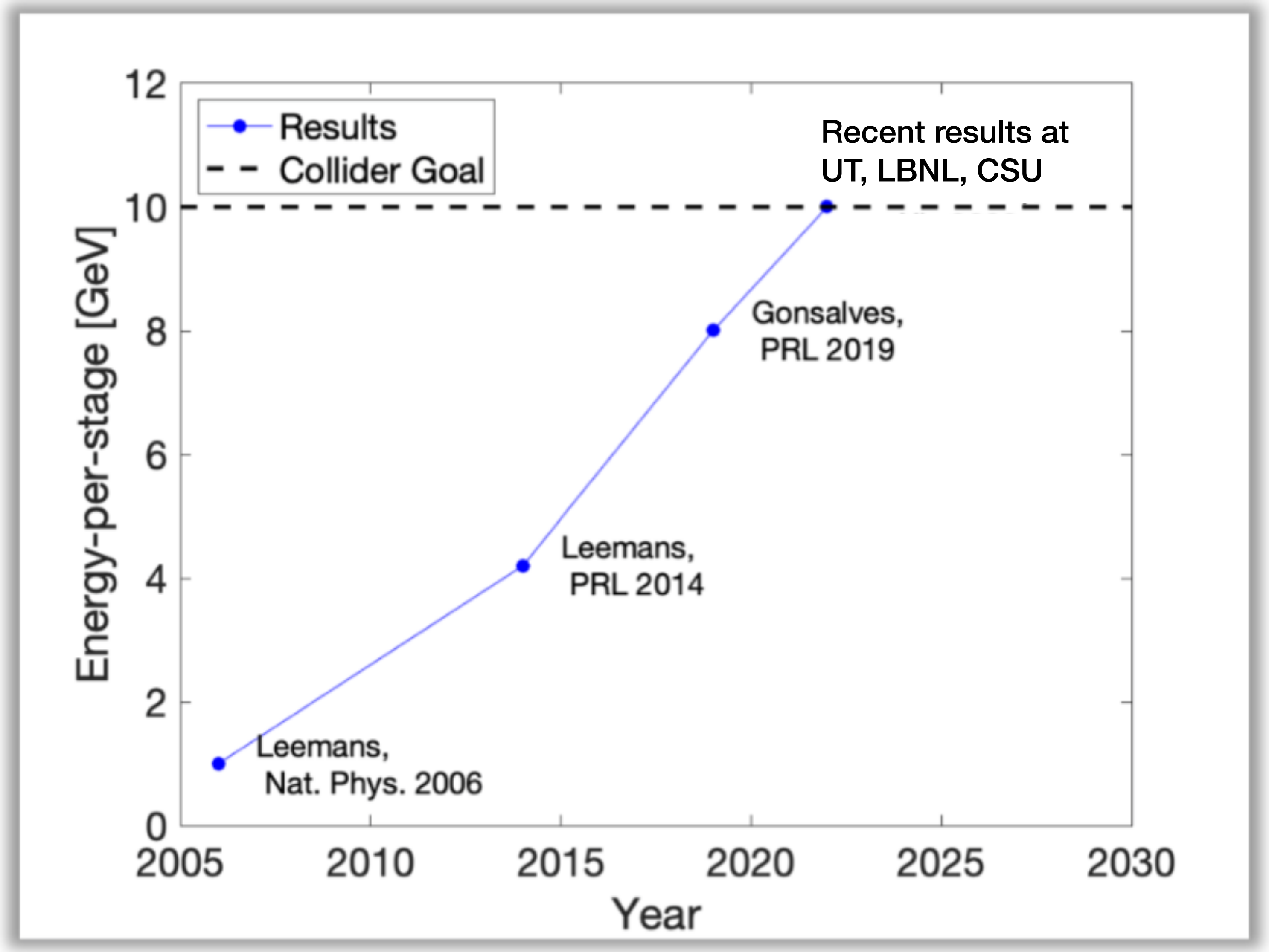


W. Wang *et al.*, Nature **595**, 516 (2021)

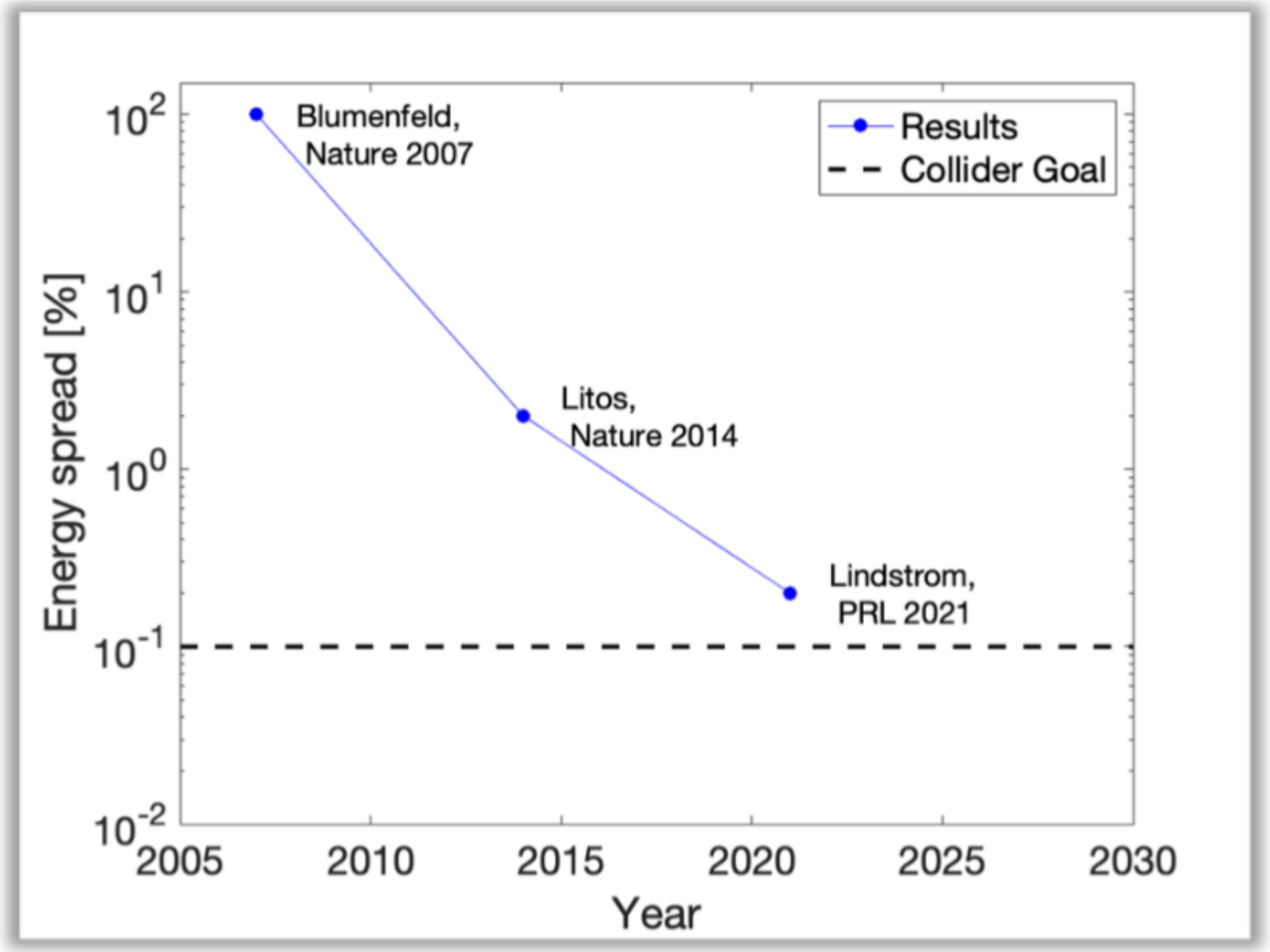
Also:
R. Pompili *et al.*, Nature **605**, 659 (2022)
M. Labat *et al.*, Nature Photonics **17**, 150 (2023)
S. Barber *et al.*, in preparation (2024)

Wakefield accelerator stages are approaching and exceeding select individual parameters for a future multi-TeV collider

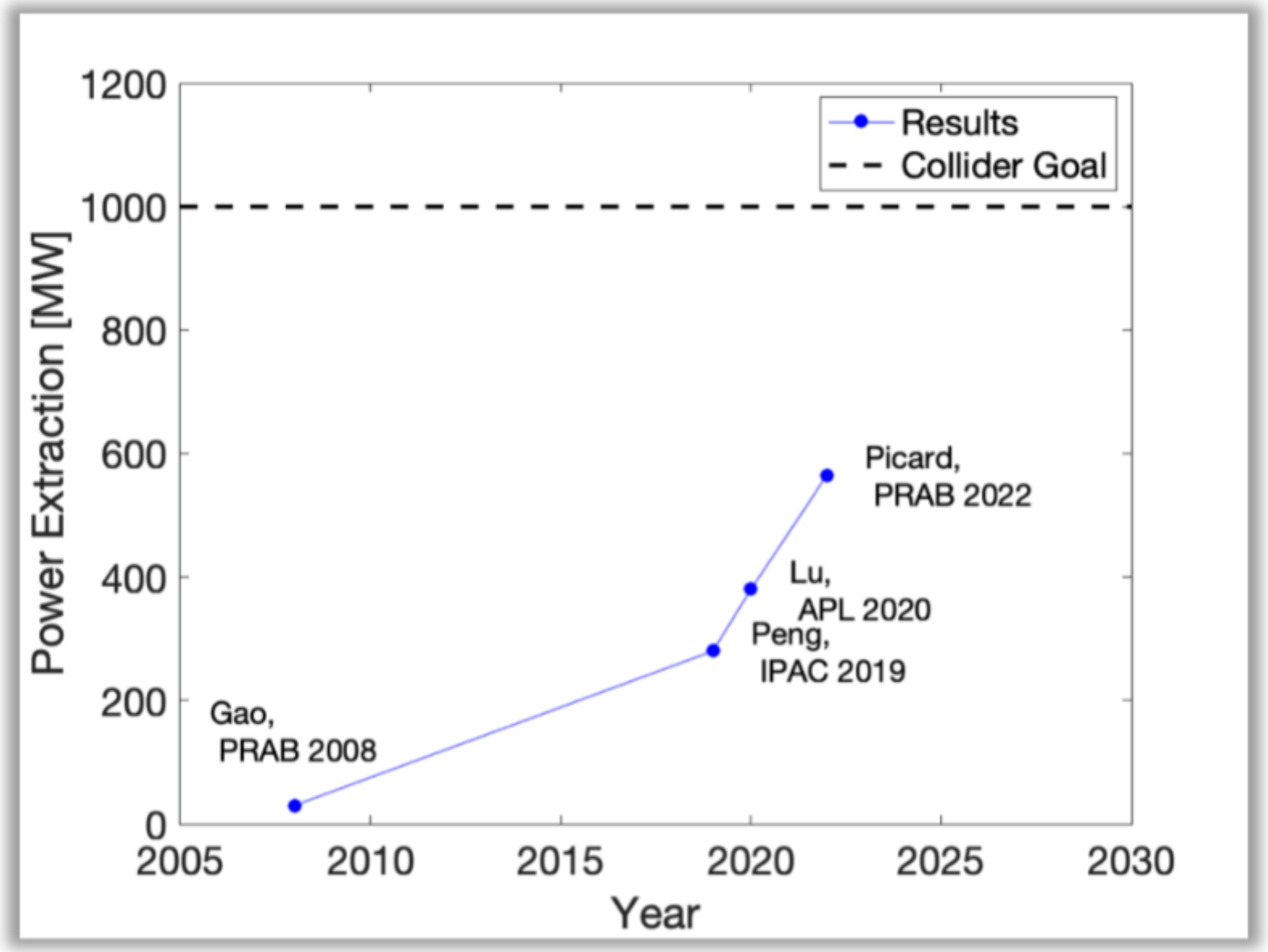
Laser-driven plasma



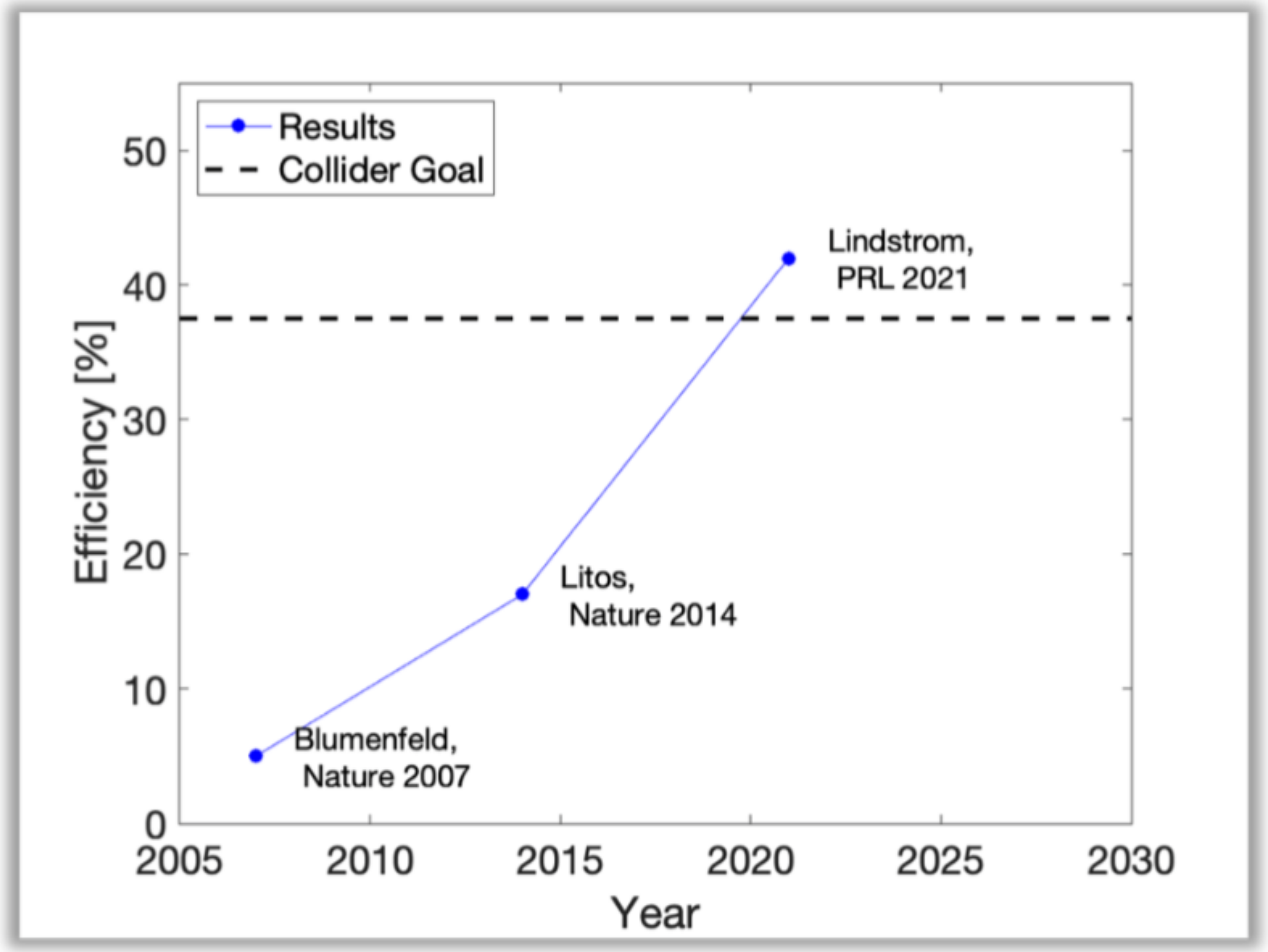
Beam-driven plasma



Structure Wakefield



Beam-driven plasma



Next steps/challenges:

- precision stage combining brightness, efficiency, alignment, stability
- coupling multiple such stages with high efficiency, tolerances
- positrons, spin transport
- compact BDS
- high average power and wall-plug efficiency

→ **test facilities are needed**

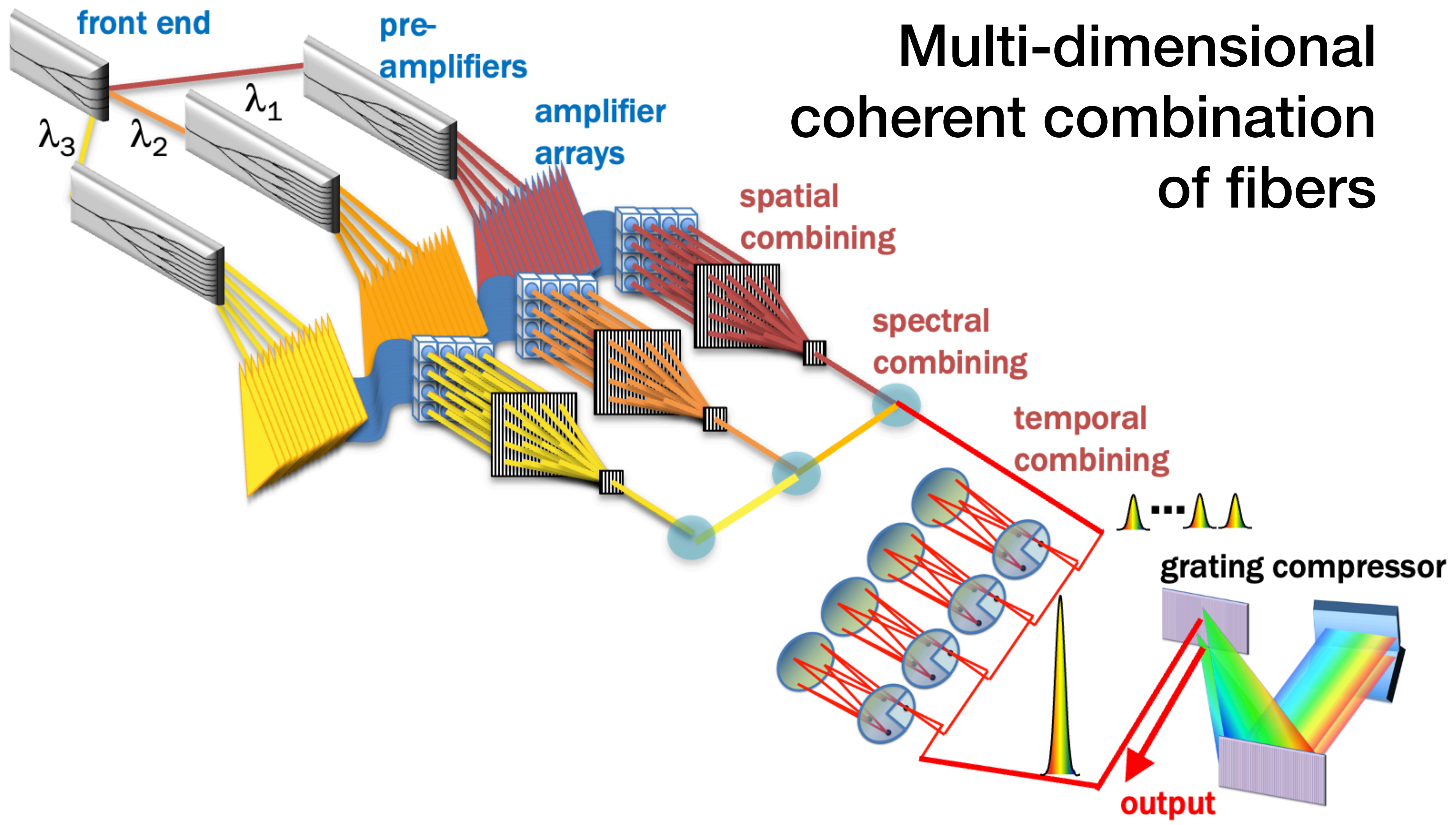
> **“In order to make a confident, informed decision on the path forward—a decision that we hope to make within the next 20 years—one or more of these technologies must reach technical maturity, allowing us to reliably estimate both cost and technical risk”**
>
> *P5 draft (2023), p. 85*

Material courtesy of Spencer Gessner (SLAC)

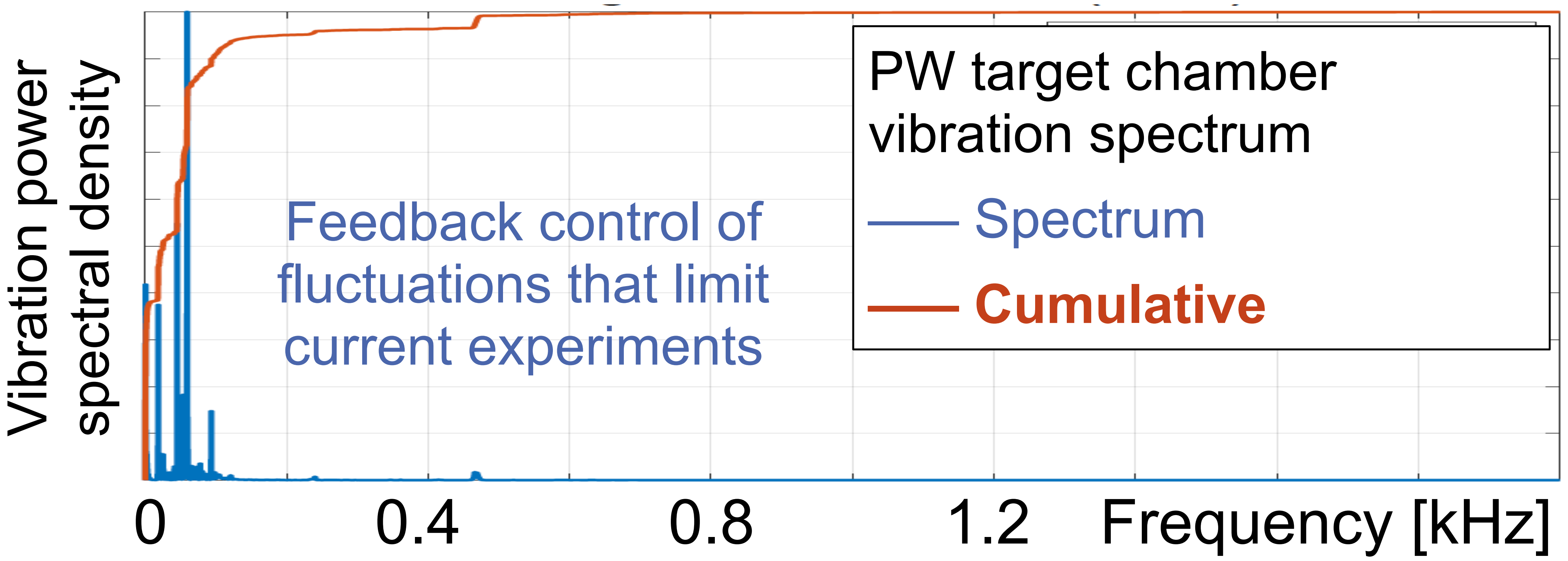
kBELLA addresses the efficiency, average power, and precision gap, essential for the technology to mature towards 10 TeV collider requirements

> *"New kW-class efficient lasers, and use of their kilohertz repetition rate for active feedback at kBELLA, will advance stage performance and enable beam tests… These (kBELLA, FACET-II, AWA), together with muon collider development, will advance the technology and feed into a future demonstrator facility to make possible a 10 TeV pCM collider (see Sec. 6.5)."*

P5 Report (2023), p. 88


Multi-dimensional coherent combination of fibers

95% of environmental vibration correctable at kHz



kBELLA will be a test facility for advanced accelerators: critical toward a 10 TeV wakefield collider

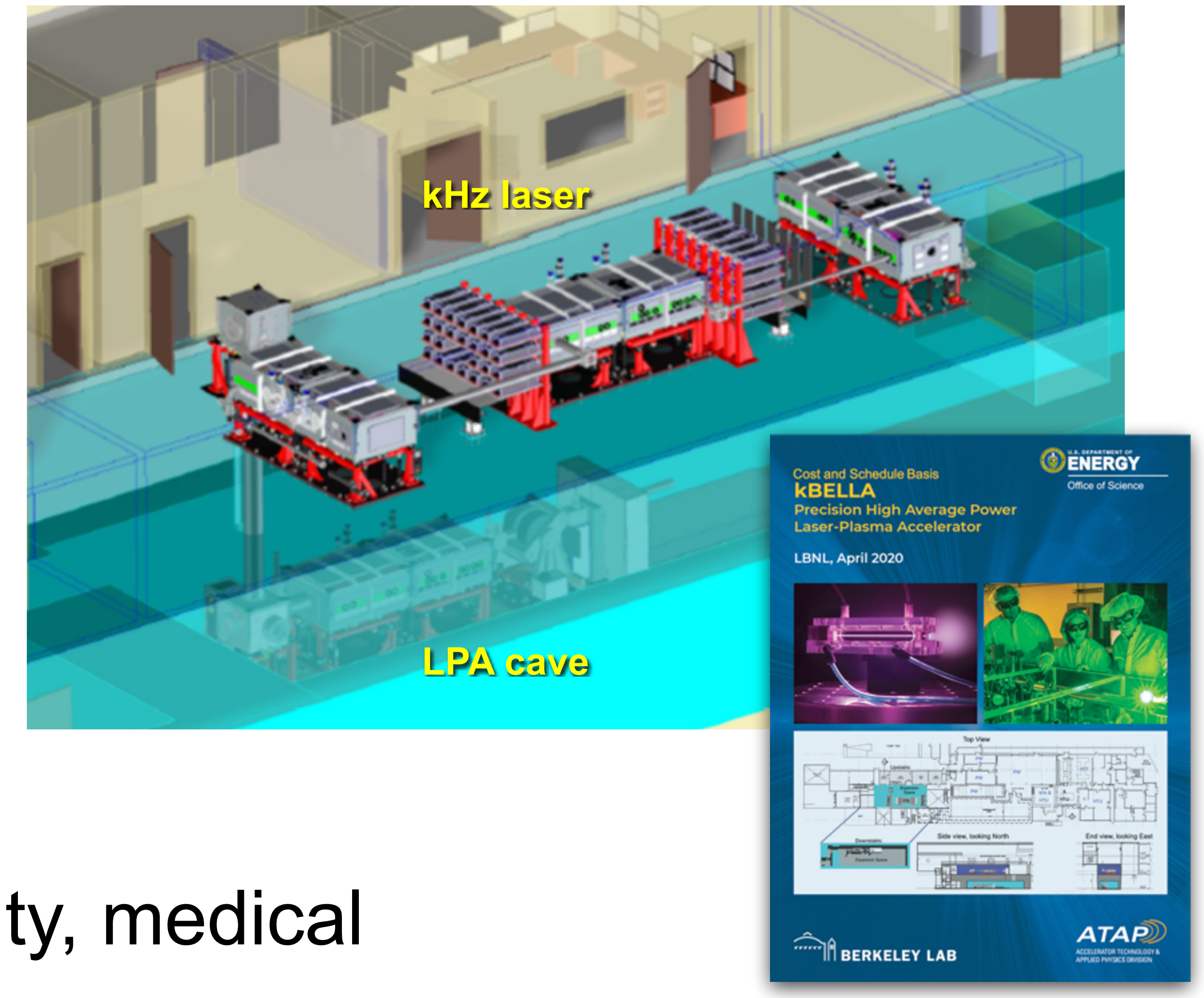
- a **high intensity, kHz+, kW short pulse laser** with 100 TW peak pwr.
- a **new facility** that provides radiation shielding for **multi-kHz-rate GeV-class plasma accelerators** and space for exp. beamlines

Enables precision LPA towards 10 TeV wakefield collider

- Test facility to address collider performance and stability needs

Enables broad impact societal and research applications

- Path to tens of kW, high efficiency, and collider demonstrator
- Competitive photon sources, security, medical

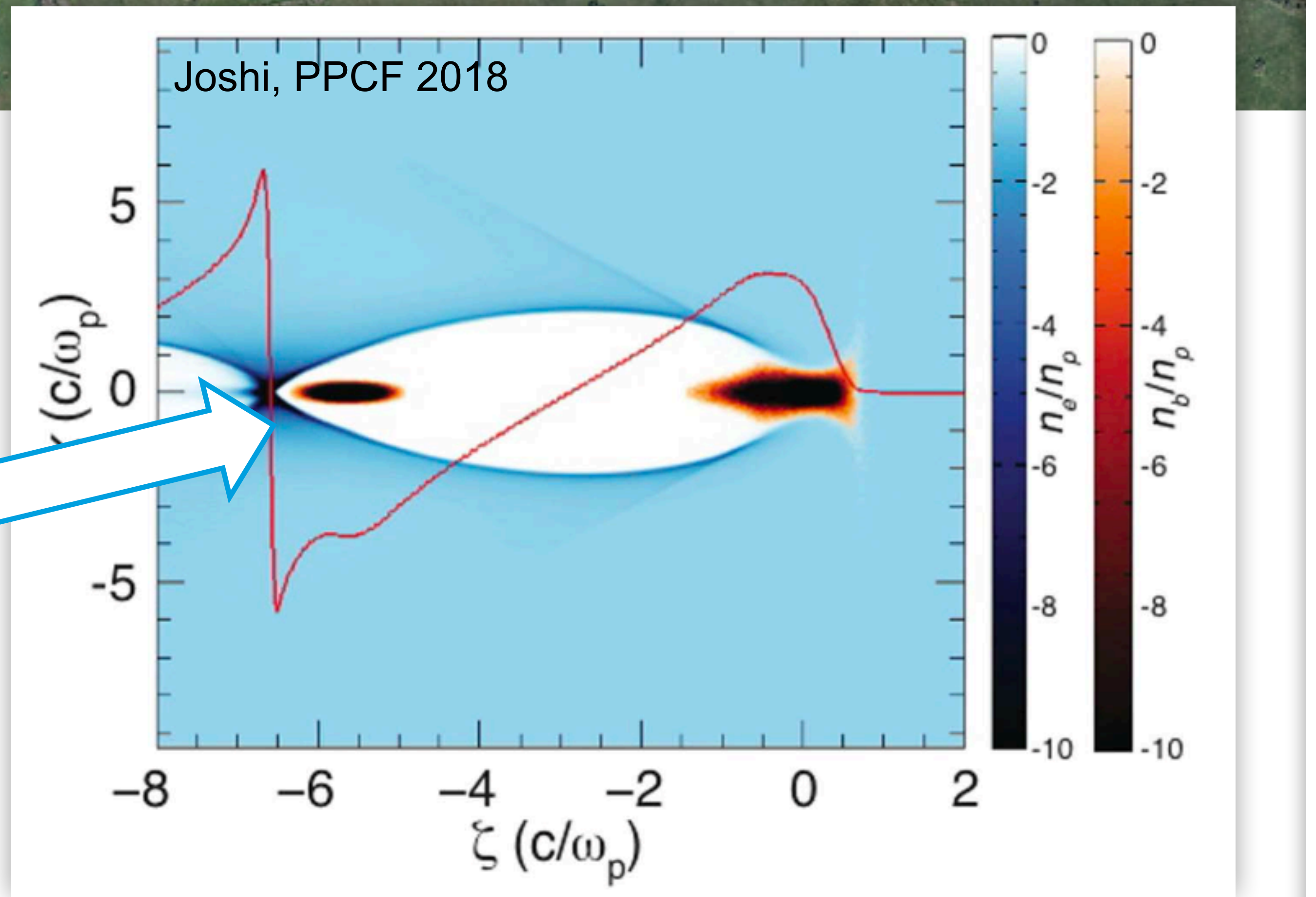


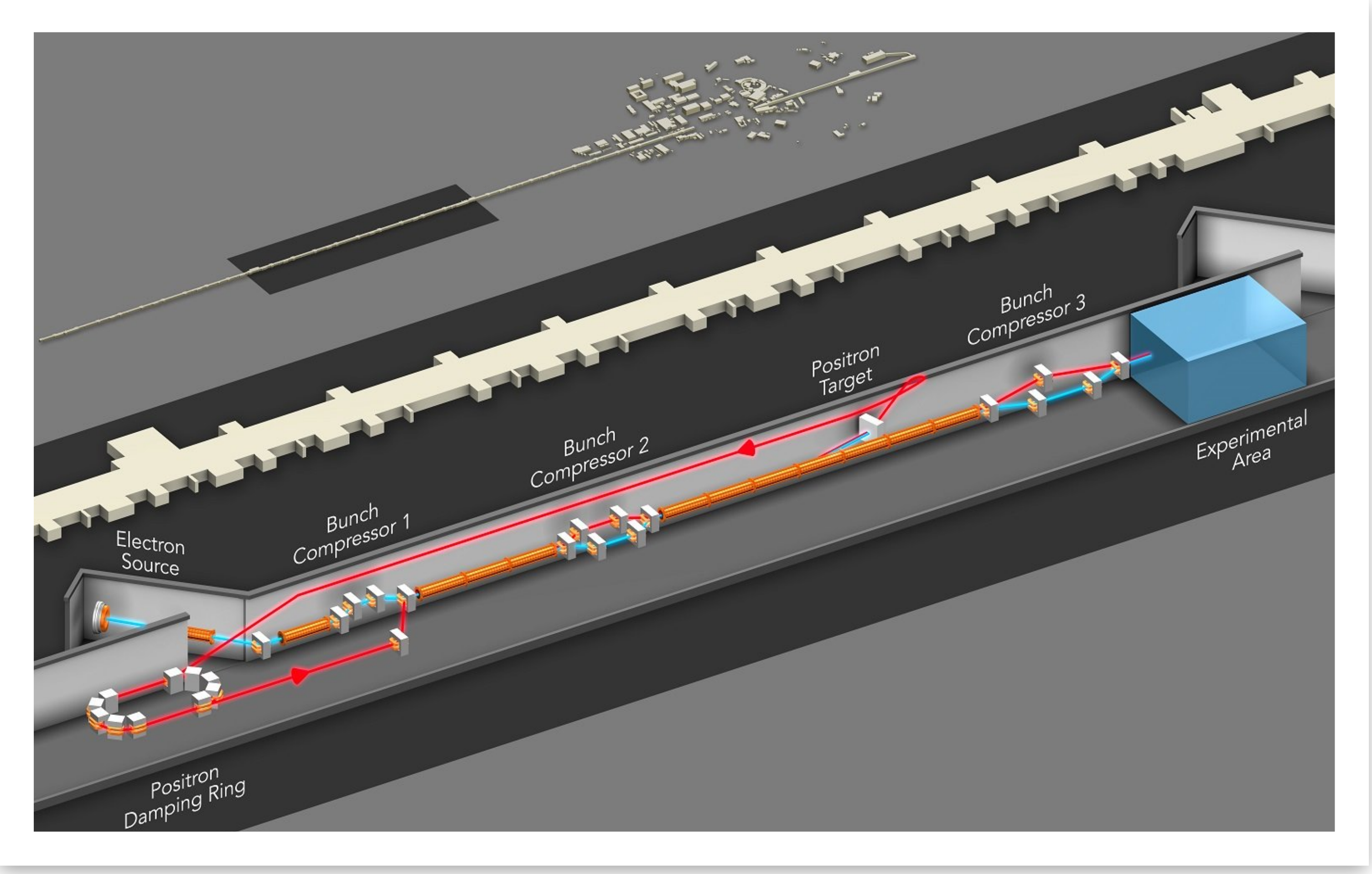
FACET-II: A world-class test beam facility

> *“An upgrade for FACET-II e⁺ is uniquely positioned to enable study of positron acceleration in high gradient plasmas.”*
>
> ***P5 Report (2023), p. 88***

What makes FACET-II unique?

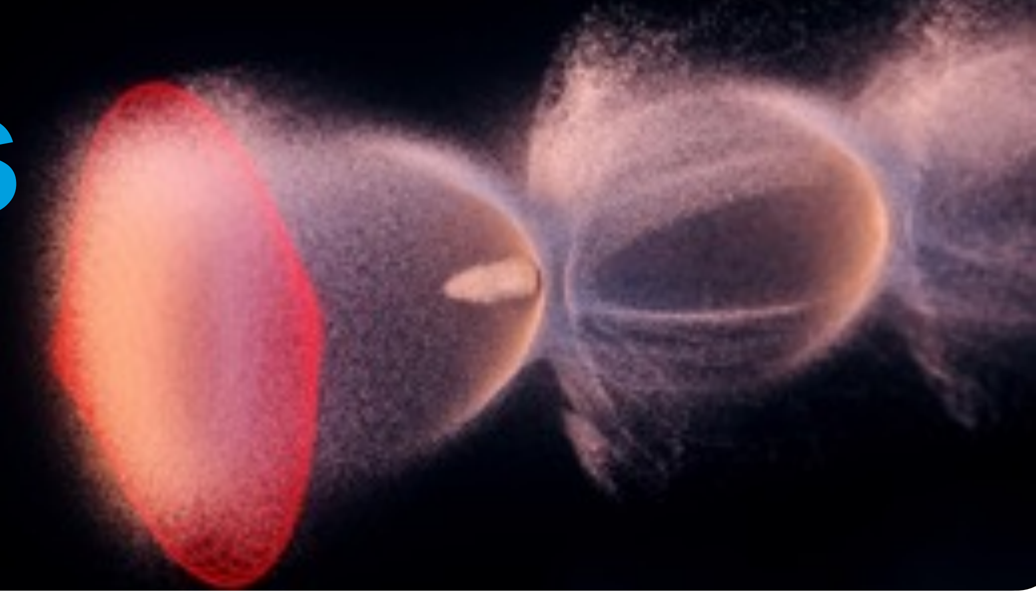
- Ultra-short bunches with ultra-high peak current.
- Precise control of the longitudinal bunch profile.
- High-power laser and plasma sources.


Joshi, PPCF 2018



Material courtesy of Mark Hogan, Spencer Gessner (SLAC)

R&D Coordination Panel: Plasma Accelerators



ESPP Roadmap exercise aims at delivering a collider pre-CDR study

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

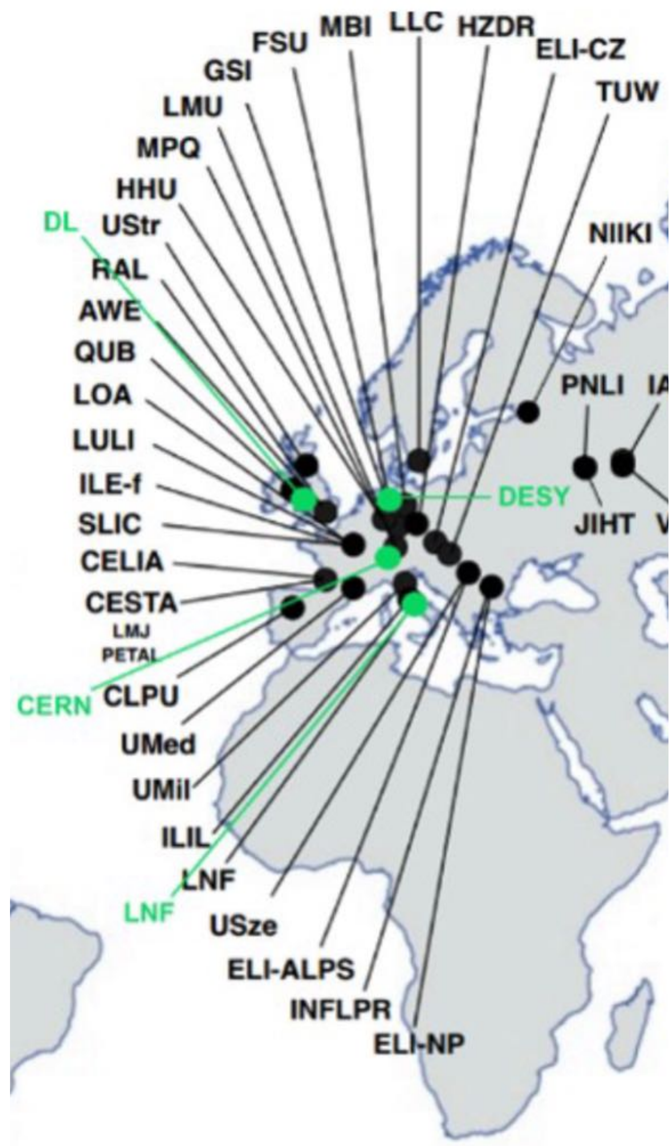
Accelerator R&D Roadmap

European Strategy Update

LDG Laboratory Directors Group

High gradient plasma and laser accelerators

Deliverable	Due by
Report: Electron High Energy Case Study (from 175GeV to 190GeV)	Jun-24
Report: Positron High Energy Case Study (similar to above)	Jun-25
Report: Spin-Polarised Beams in Plasma Accelerators	Dec-25
Report: Physics Case of an Advanced Collider	Jun-24
Report: Low Energy Study Cases for Electrons and Positrons (15-50GeV)	Jun-25
Report: Pre-CDR and Collider Feasibility Report	Dec-25
Experiment: High-Repetition Rate (Laser) Plasma Accelerator Module (kHz)	Dec-25
Experiment: High-Efficiency, Electron/Proton-Driven Plasma Accelerator Module with High Beam Quality	Dec-25

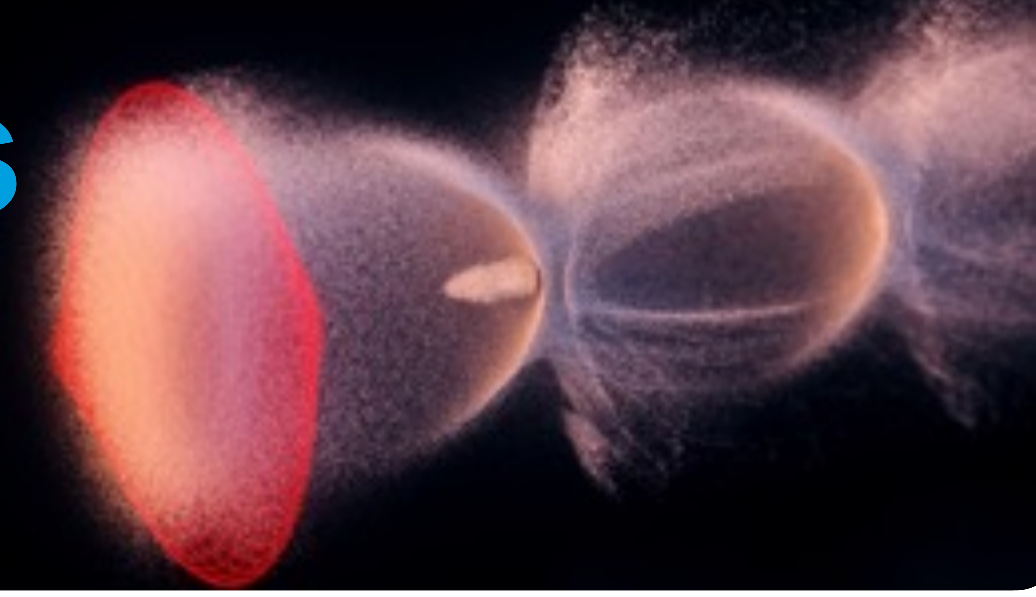


- Current European research in laser- and beam-driven plasma accelerators concentrated on producing high-quality beams for light sources and their applications
- Dedicated R&D is critical for a future plasma-based collider
- **Need a program (and funding)**

Test facilities

AWAKE
EPAC
EuPRAXIA
FF>>
KALDERA
PIP4
SPARC
…

R&D Coordination Panel: Plasma Accelerators



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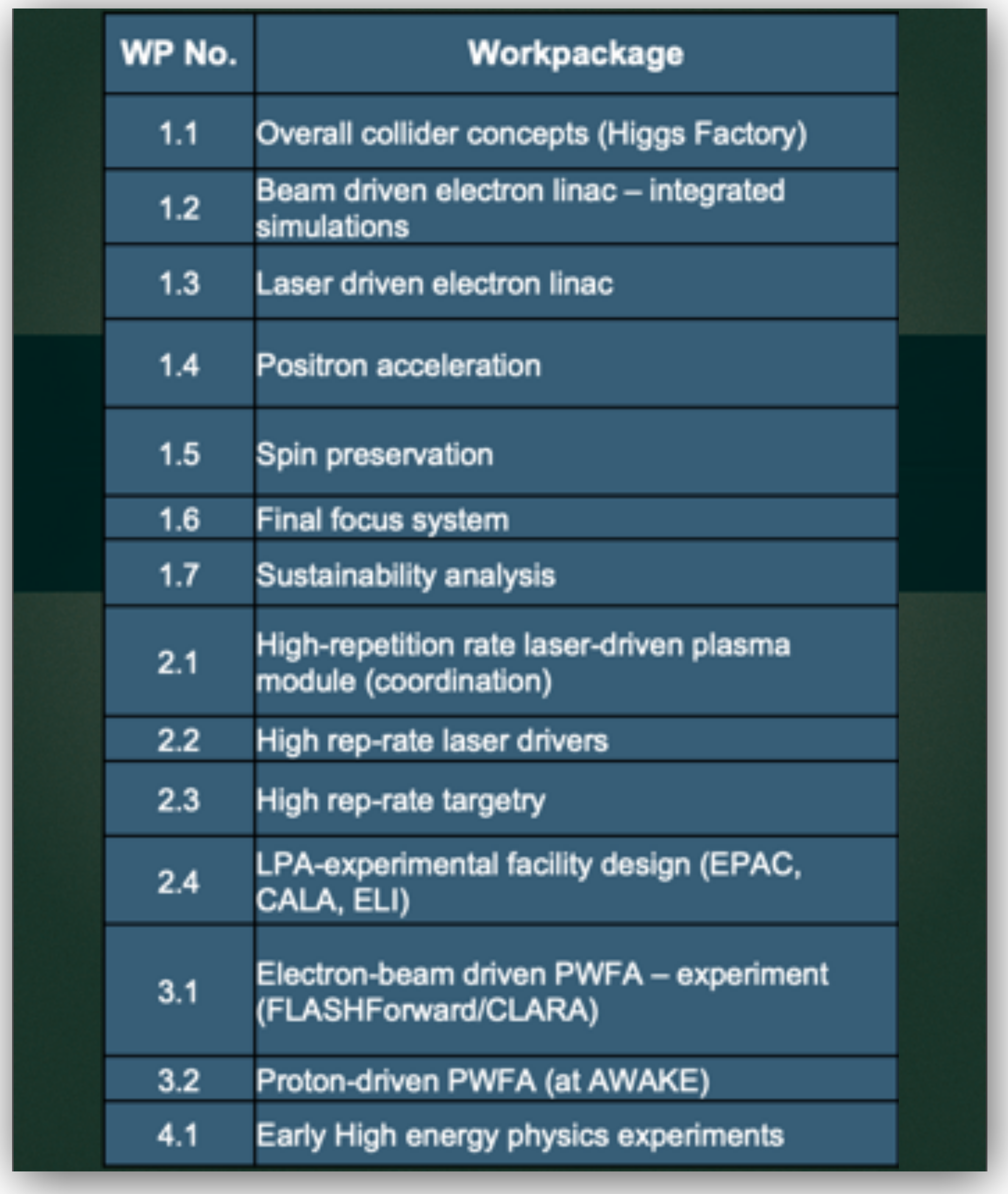

WP No.	Workpackage
1.1	Overall collider concepts (Higgs Factory)
1.2	Beam driven electron linac – integrated simulations
1.3	Laser driven electron linac
1.4	Positron acceleration
1.5	Spin preservation
1.6	Final focus system
1.7	Sustainability analysis
2.1	High-repetition rate laser-driven plasma module (coordination)
2.2	High rep-rate laser drivers
2.3	High rep-rate targetry
2.4	LPA-experimental facility design (EPAC, CALA, ELI)
3.1	Electron-beam driven PWFA – experiment (FLASHForward/CLARA)
3.2	Proton-driven PWFA (at AWAKE)
4.1	Early High energy physics experiments

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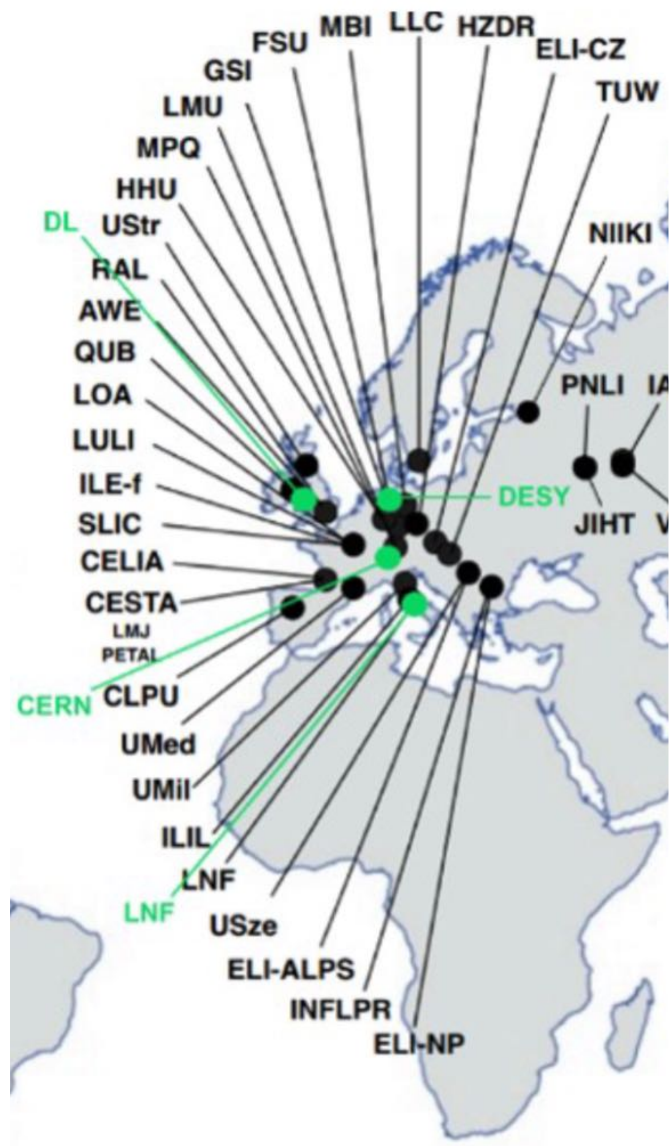

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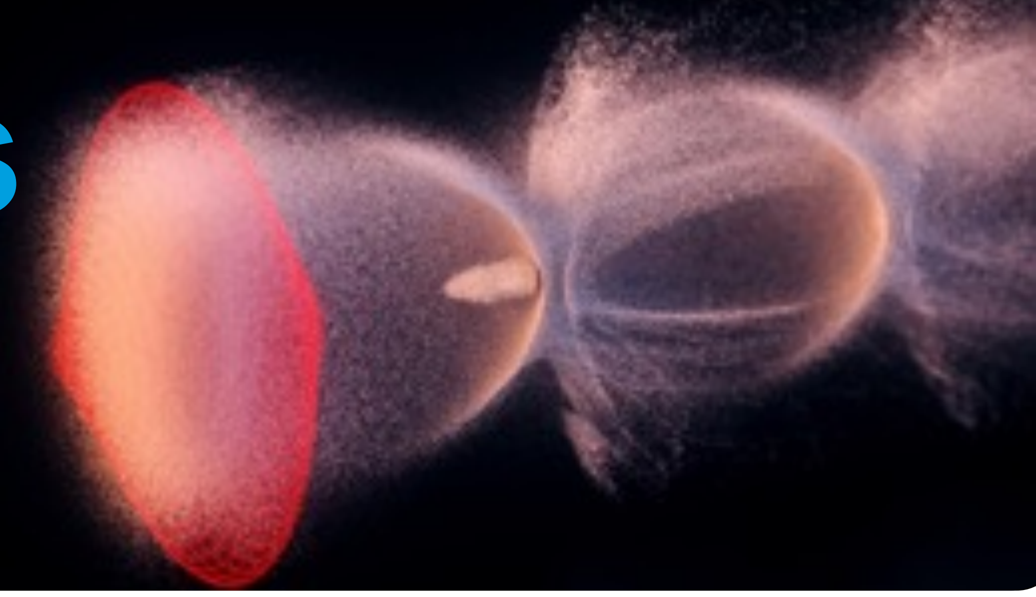

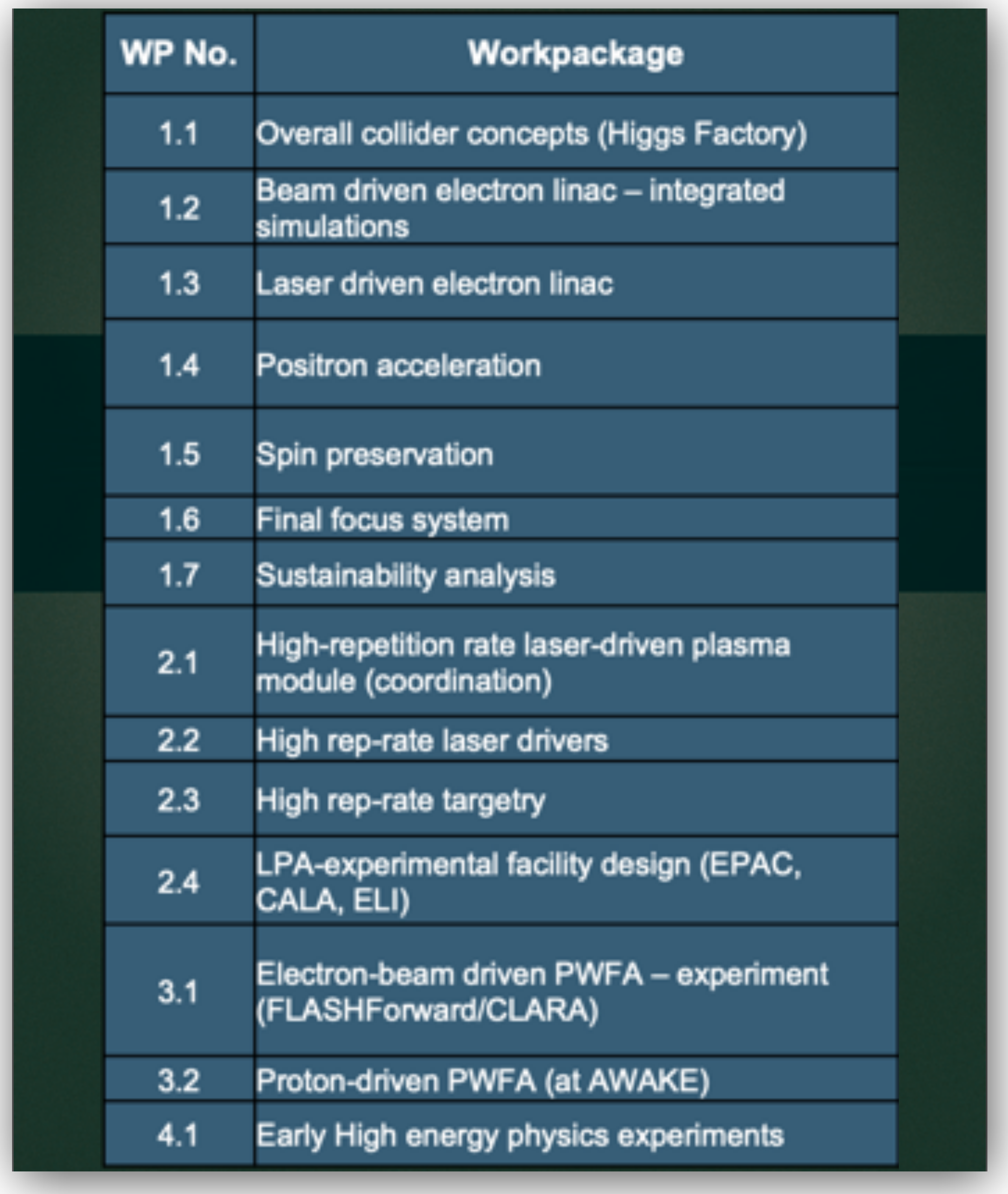

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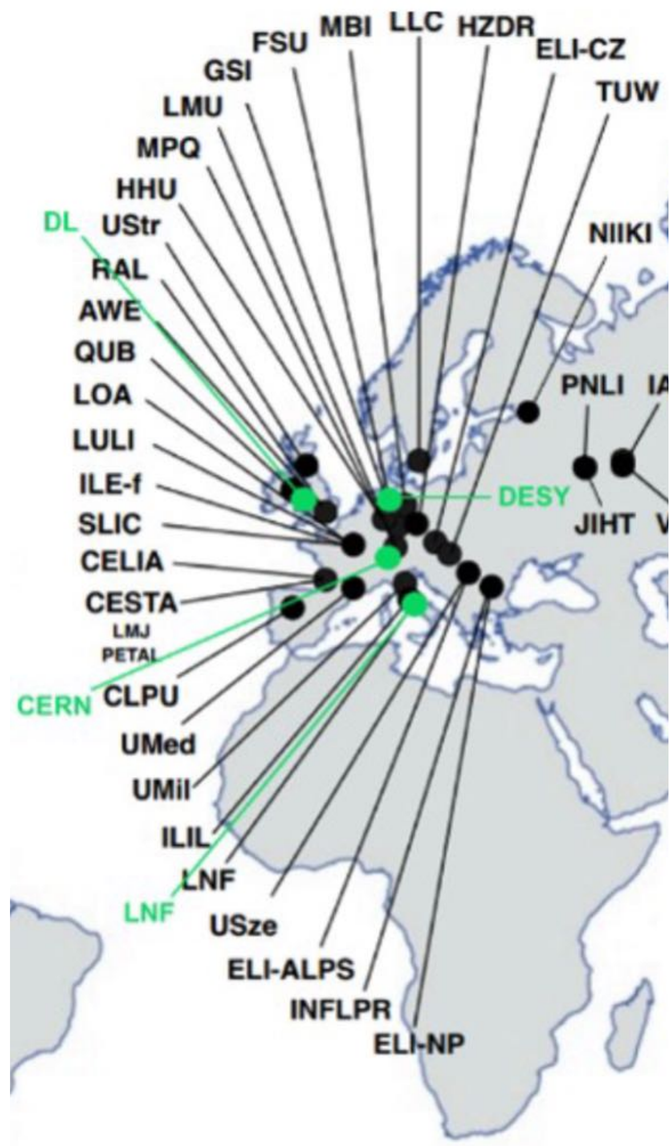
Report: Electron High Energy Case Study (from 175GeV to 190GeV)	Jun-24
Report: Positron High Energy Case Study (similar to above)	Jun-25
Report: Spin-Polarised Beams in Plasma Accelerators	Dec-25
Report: Physics Case of an Advanced Collider	Jun-24
Report: Low Energy Study Cases for Electrons and Positrons (15-50GeV)	Jun-25
Report: Pre-CDR and Collider Feasibility Report	Dec-25
Experiment: High-Repetition Rate (Laser) Plasma Accelerator Module (kHz)	Dec-25
Experiment: High-Efficiency, Electron/Proton-Driven Plasma Accelerator Module with High Beam Quality	Dec-25



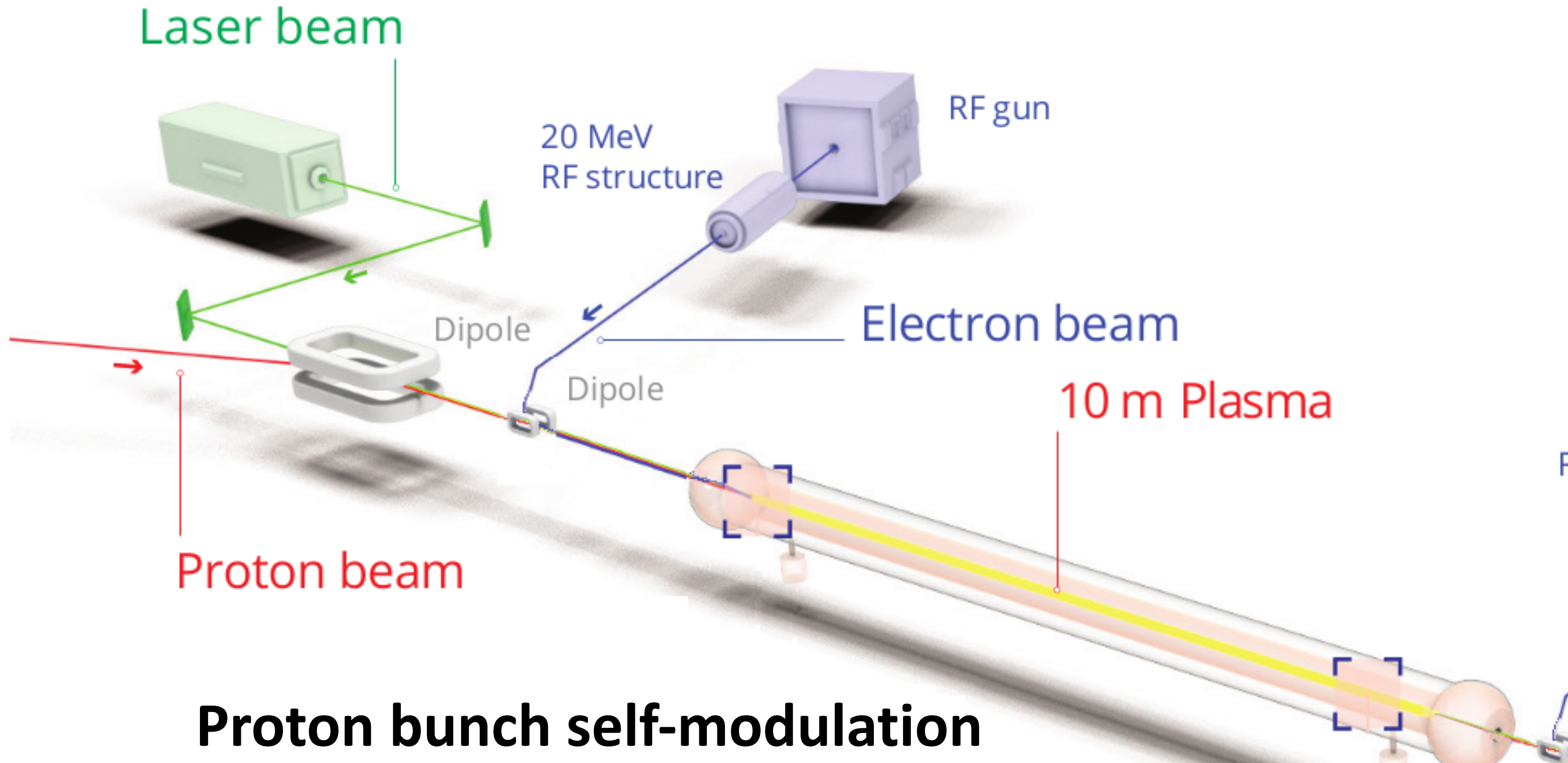
- Current European research in laser- and beam-driven plasma accelerators concentrated on producing high-quality beams for light sources and their applications
- Dedicated R&D is critical for a future plasma-based collider
- **Need a program (and funding)**
- **AWAKE at CERN has a funded, programmatic path for particle physics applications and plasma accelerator challenges**

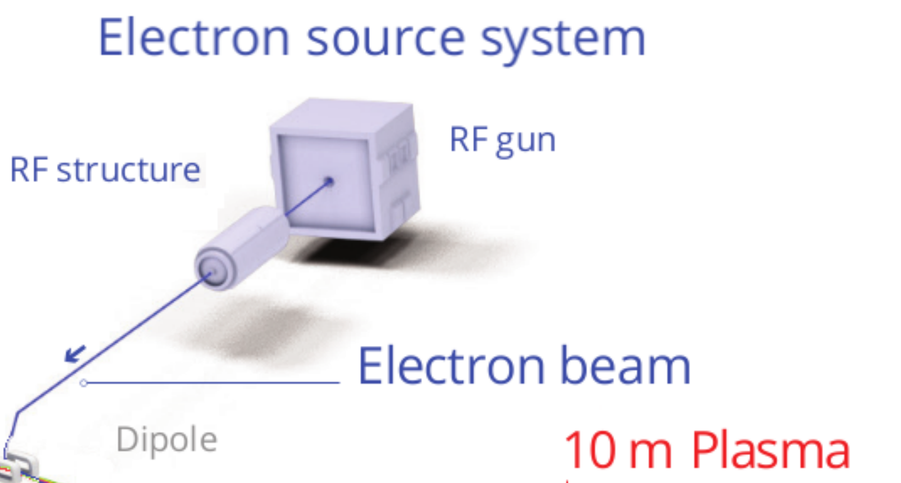
HALHF

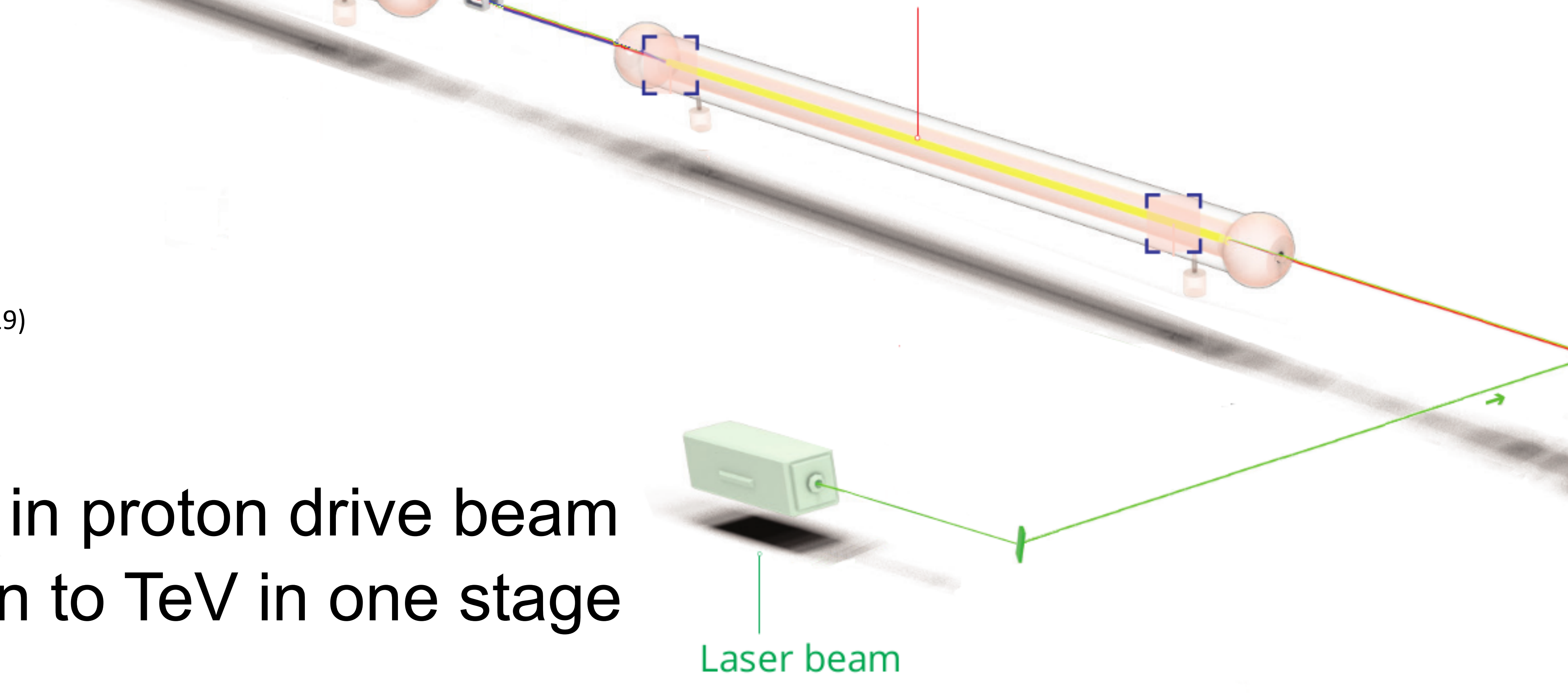
A hybrid, asymmetric, linear Higgs factory

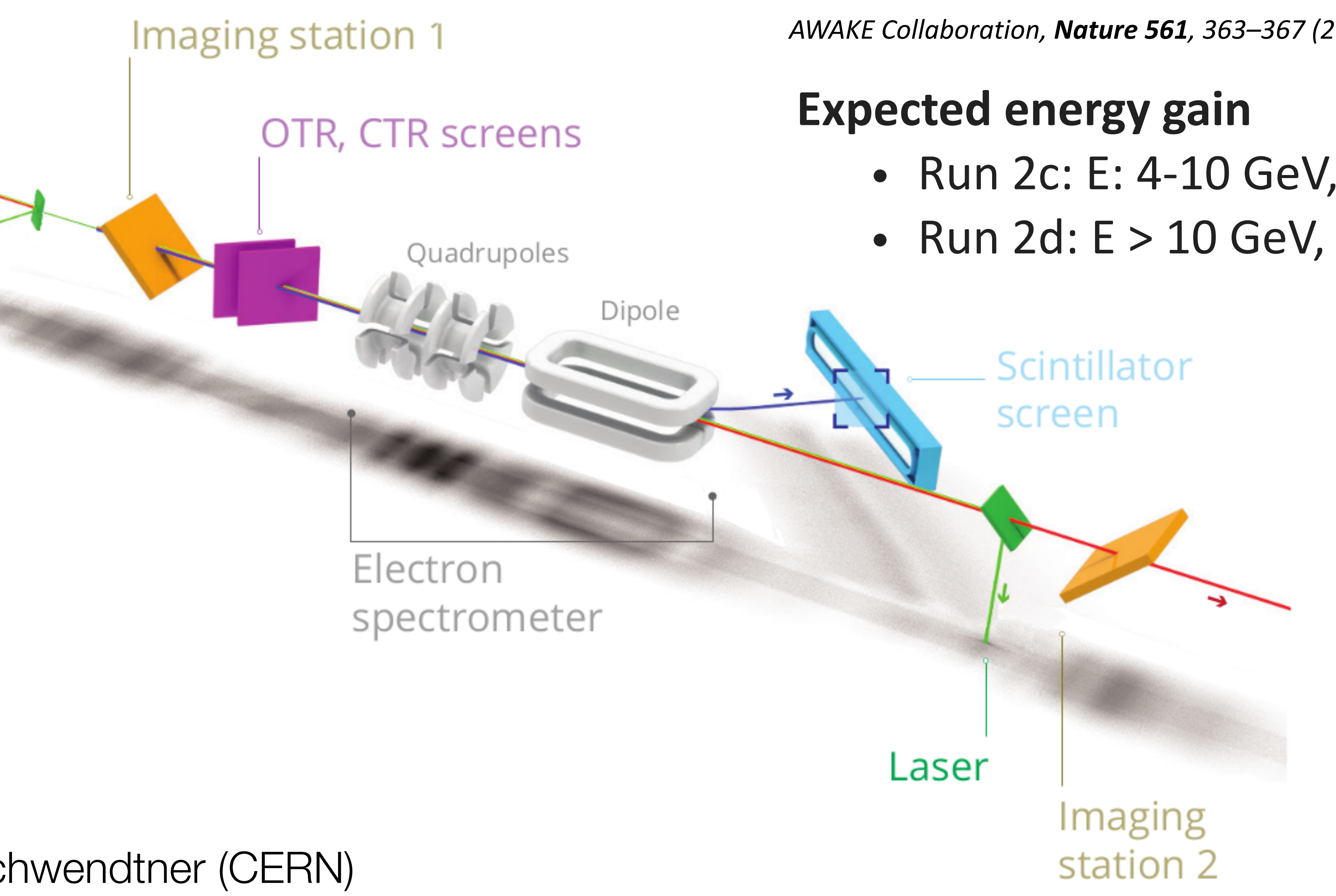
All the details: next talk by R.D'Arcy and C.A.Lindstrøm

AWAKE — proton-driven PWFA experiment removes staging need

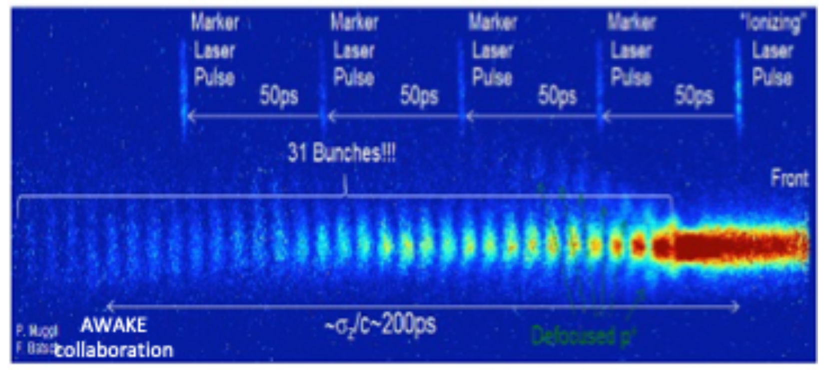






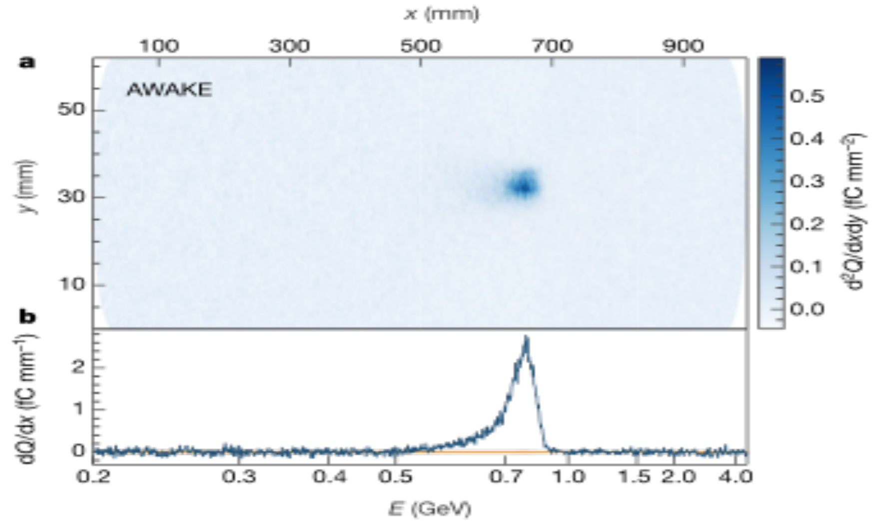


Proton bunch self-modulation

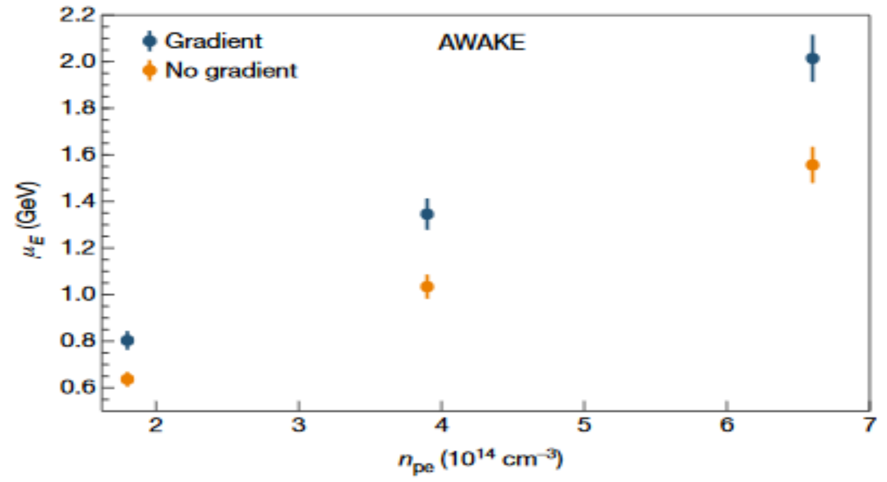


AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019)

Accelerated electrons



Increase e-energy with density gradients



*AWAKE Collaboration, **Nature 561**, 363–367 (2018)*

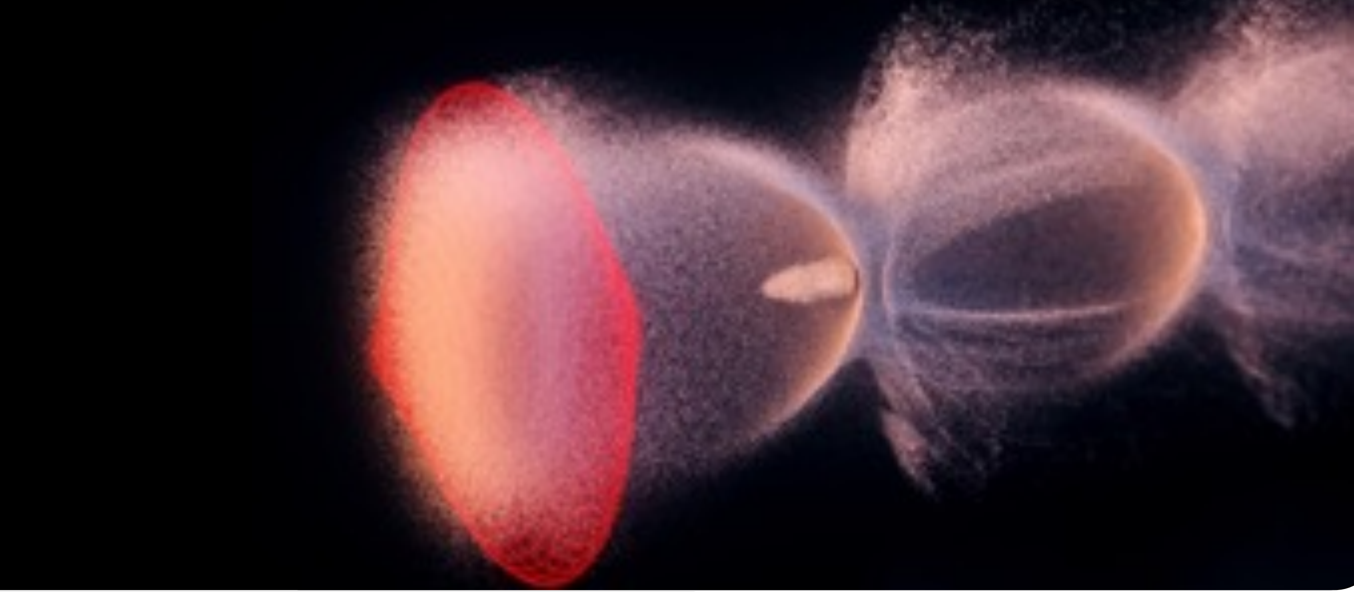
Expected energy gain

- Run 2c: E: 4-10 GeV, 10m
- Run 2d: E > 10 GeV, 10+ m

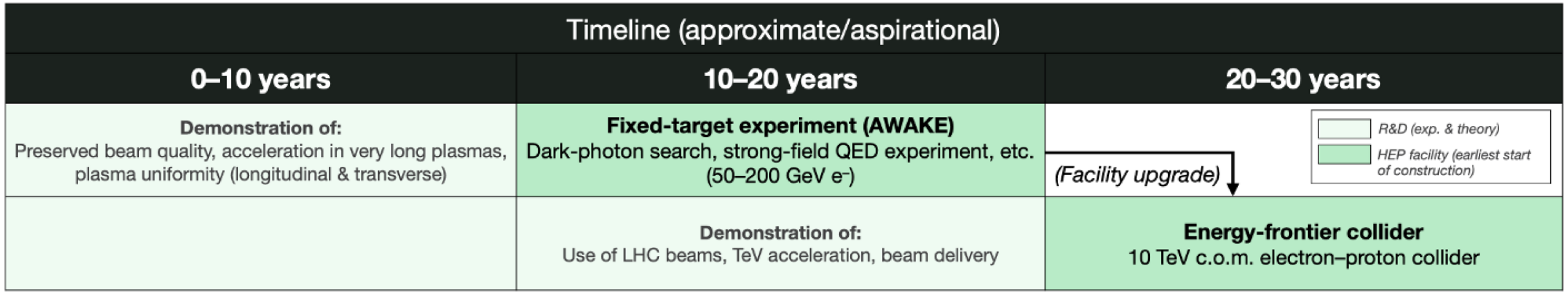
- 19 kJ of stored energy in proton drive beam
→ electron acceleration to TeV in one stage
- Highly successful experimental program
- *Next steps:*
AWAKE Run 2 — beam quality and energy scalability approved

Material courtesy of E. Gschwendtner (CERN)

Aspirational timelines for European R&D on plasma-based colliders

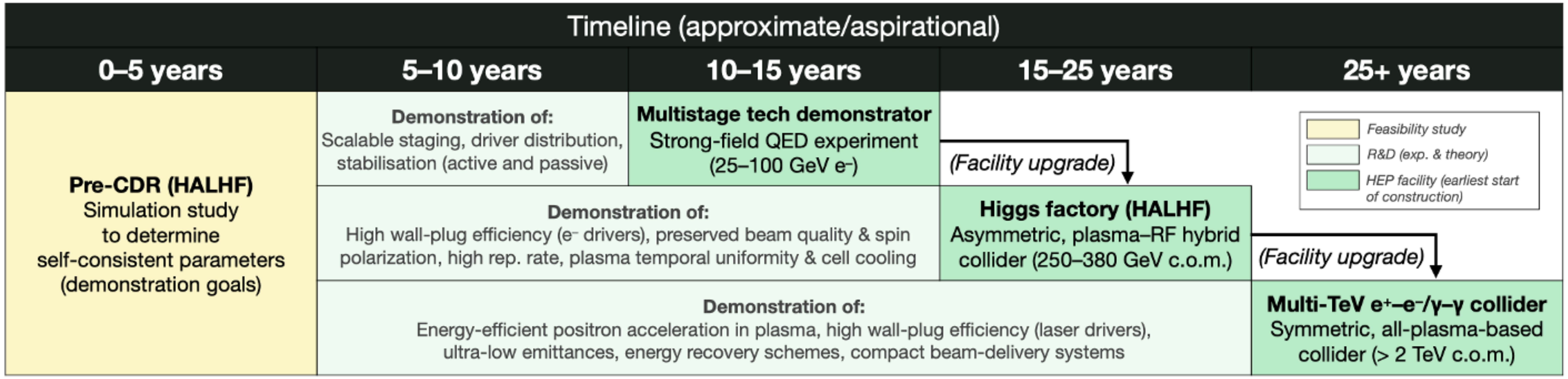


Single-stage accelerators
(proton-driven)



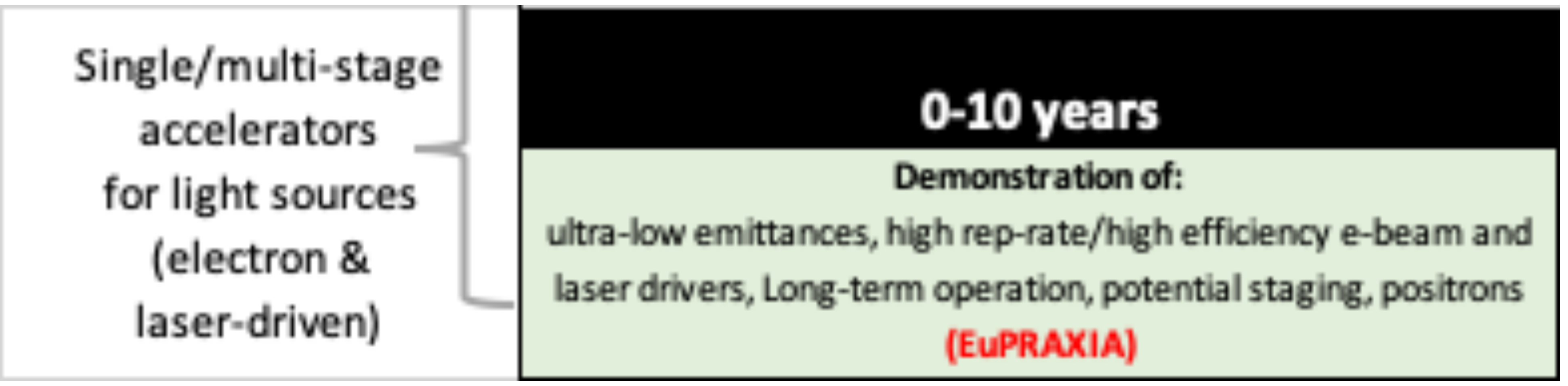
Timeline (approximate/aspirational)		
0–10 years	**10–20 years**	**20–30 years**
Demonstration of: Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon search, strong-field QED experiment, etc. (50–200 GeV e^-)	*(Facility upgrade)* ☐ *R&D (exp. & theory)* 🟩 *HEP facility (earliest start of construction)*
	Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy-frontier collider** 10 TeV c.o.m. electron–proton collider

Multistage accelerators
(Electron-driven or laser-driven)



Timeline (approximate/aspirational)				
0–5 years	**5–10 years**	**10–15 years**	**15–25 years**	**25+ years**
Pre-CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** Scalable staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25–100 GeV e^-)	*(Facility upgrade)*	🟨 *Feasibility study* ☐ *R&D (exp. & theory)* 🟩 *HEP facility (earliest start of construction)*
	Demonstration of: High wall-plug efficiency (e^- drivers), preserved beam quality & spin polarization, high rep. rate, plasma temporal uniformity & cell cooling		**Higgs factory (HALHF)** Asymmetric, plasma–RF hybrid collider (250–380 GeV c.o.m.)	*(Facility upgrade)*
	Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser drivers), ultra-low emittances, energy recovery schemes, compact beam-delivery systems			**Multi-TeV e^+–e^-/γ–γ collider** Symmetric, all-plasma-based collider (> 2 TeV c.o.m.)

HALHF



Single/multi-stage accelerators for light sources (electron & laser-driven)	0-10 years
	Demonstration of: ultra-low emittances, high rep-rate/high efficiency e-beam and laser drivers, Long-term operation, potential staging, positrons (EuPRAXIA)

R&D on EuPRAXIA will de-risk HALHF and other plasma-based collider concepts considerably

Pursuit of plasma wakefield R&D complementary in US and Europe

Potential for leveraging strong synergies by connecting/coordinating US and European efforts

- **Plasma wakefield accelerators are continuing to progress at a rapid pace,** have recently demonstrated beam parameters for photon science applications
- **Progress toward colliders encouraging** — challenges remain: efficiency, avg. power, multi-staging, …
- New scheme, HALHF, demonstrates cost saving potential, introduces plasma collider design processes
- P5 sets focus on a 10 TeV pCM collider, no tech ready, wakefields are a contender, design launched
- **We need intense R&D and test facilities to close the existing technology capability gaps for HALHF + 10 TeV collider**
- **Intensified coordination/collaboration on collider designs, technology, test facilities, demonstrators between US and European communities will be mutually beneficial and is synergistic**
    - Goals may differ, but physics/tech challenges and processes (e.g. cost models) strongly linked
    - Realizing a collider incl. needed resources is a global effort