Wakefield Accelerators: The Path to 10 TeV and Beyond

Spencer Gessner, Staff Scientist
SLAC National Accelerator Laboratory

P5 Townhall, May 3, 2023

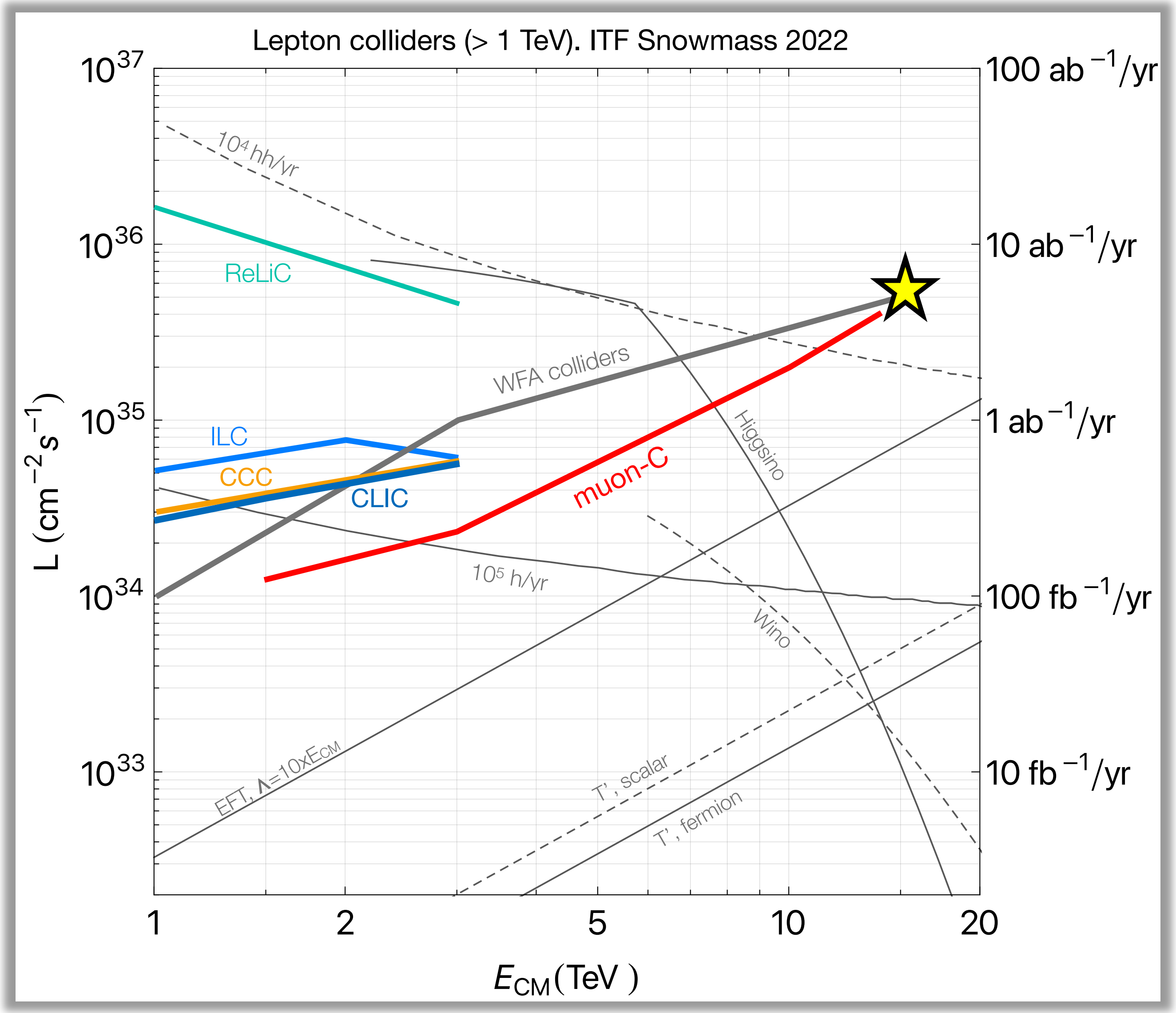
With input from:
J. Power, P. Piot, C. Jing, X. Lu,
J.L. Vay, J. van Tilborg, T. Gonsalves,
C. Schroeder, E. Esarey, M. Hogan
and
Snowmass AF6 Advanced Accelerator Frontier

SLAC NATIONAL ACCELERATOR LABORATORY
Stanford University
U.S. DEPARTMENT OF ENERGY

Physics Motivation

Energy Frontier Executive Summary

While the naturalness principle suggests new physics to lie at mass scales close to the electroweak scale, in many cases direct searches for specific models have placed strong bounds around 1-2 TeV. Thus, the energy frontier has moved beyond the TeV scale and the exploration of the 10 TeV scale becomes crucial to shed light on physics beyond the Standard Model (SM).



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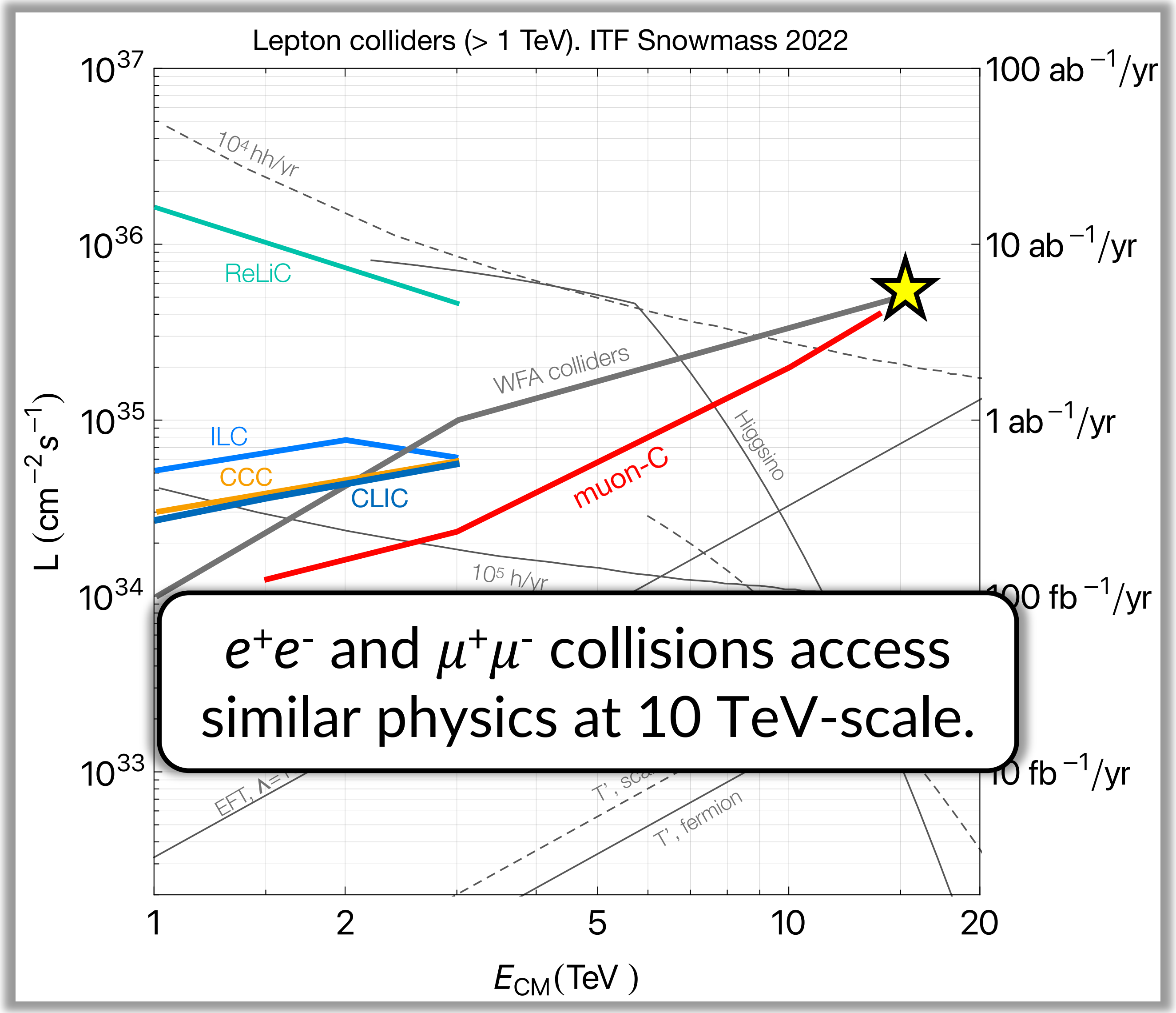
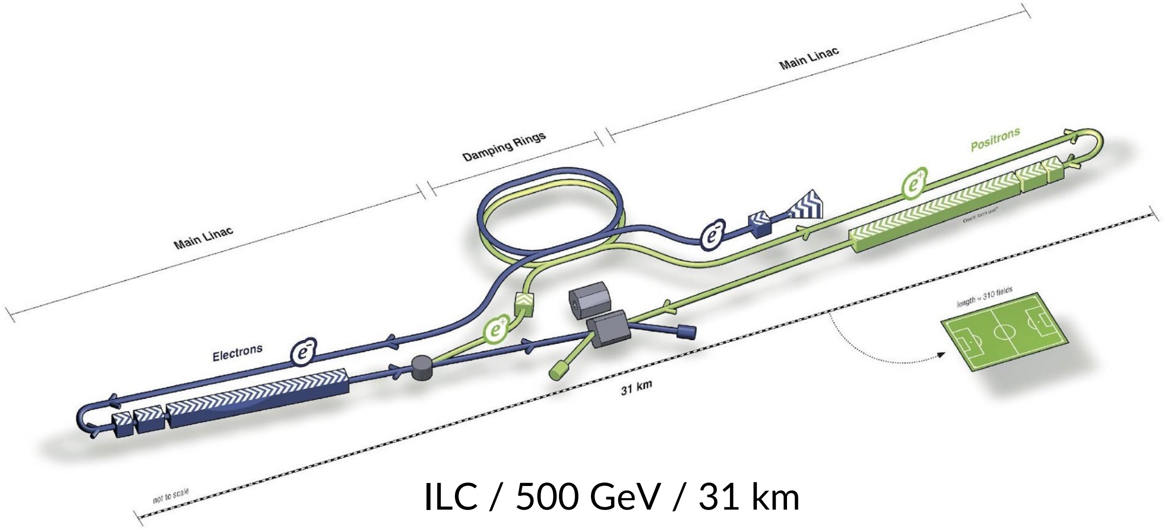


e^+e^- and $\mu^+\mu^-$ collisions access similar physics at 10 TeV-scale.

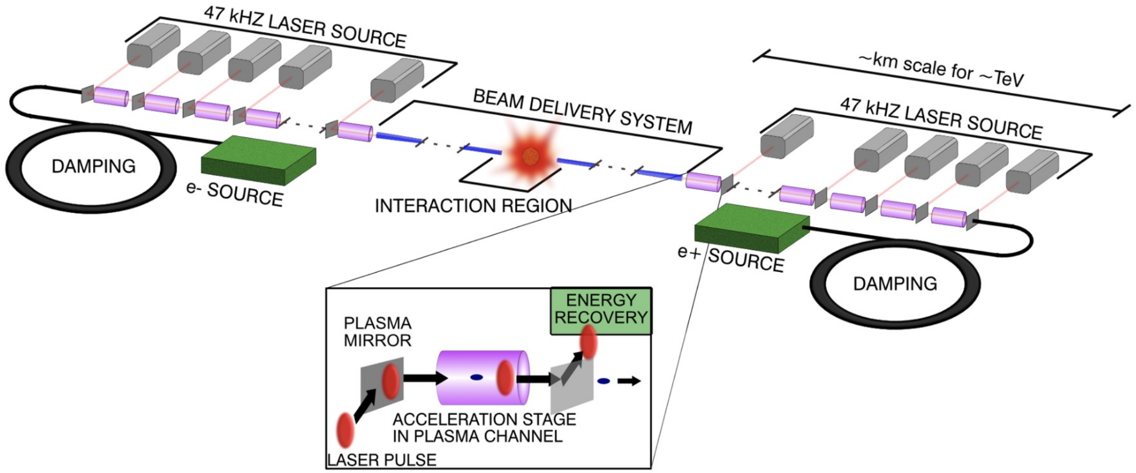
Wakefield Accelerator Mission

Three goals:

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



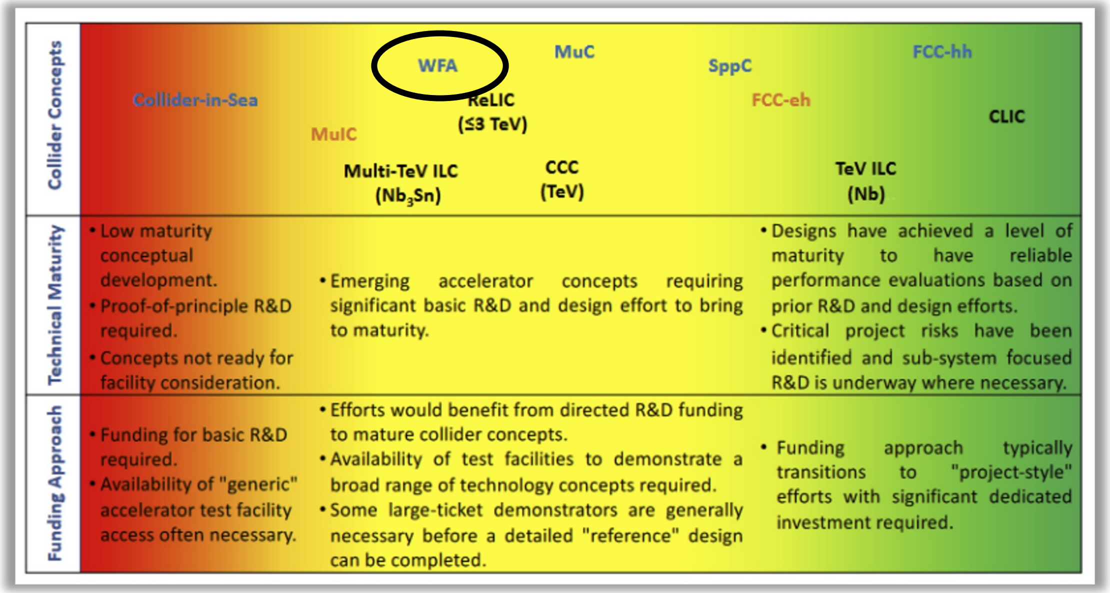
ILC / 500 GeV / 31 km



Plasma Collider / 15 TeV / 6.6 km

Near-Term Outlook

Snowmass AF4 Energy Frontier Colliders



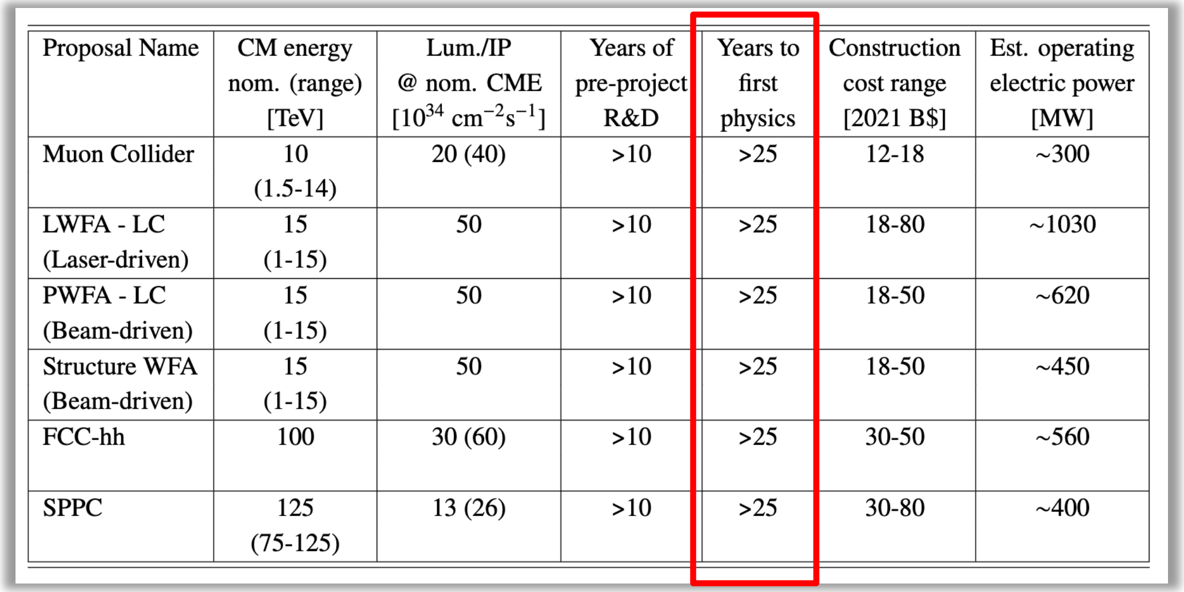
Collider Concepts

Collider-in-Sea
MuIC
WFA
ReLIC (≤3 TeV)
Multi-TeV ILC (Nb_3Sn)
MuC
CCC (TeV)
SppC
FCC-eh
FCC-hh
TeV ILC (Nb)
CLIC

Technical Maturity	- Low maturity conceptual development. - Proof-of-principle R&D required. - Concepts not ready for facility consideration.	- Emerging accelerator concepts requiring significant basic R&D and design effort to bring to maturity.	- Designs have achieved a level of maturity to have reliable performance evaluations based on prior R&D and design efforts. - Critical project risks have been identified and sub-system focused R&D is underway where necessary.
Funding Approach	- Funding for basic R&D required. - Availability of "generic" accelerator test facility access often necessary.	- Efforts would benefit from directed R&D funding to mature collider concepts. - Availability of test facilities to demonstrate a broad range of technology concepts required. - Some large-ticket demonstrators are generally necessary before a detailed "reference" design can be completed.	- Funding approach typically transitions to "project-style" efforts with significant dedicated investment required.

Less mature ⟷ More mature

Snowmass Implementation Task Force

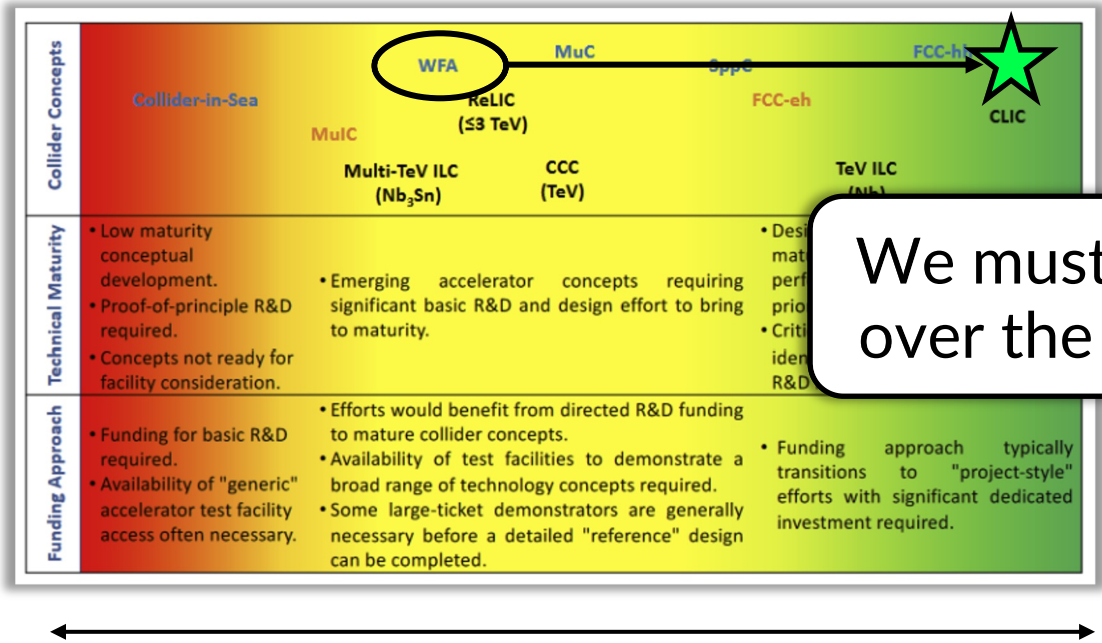


Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

Regardless of size, cost, and environmental impact, the Snowmass AF4 and ITF Frontiers concluded there are no near-term technologies for reaching 10 TeV parton-scale collisions.

Near-Term Outlook

Snowmass AF4 Energy Frontier Colliders



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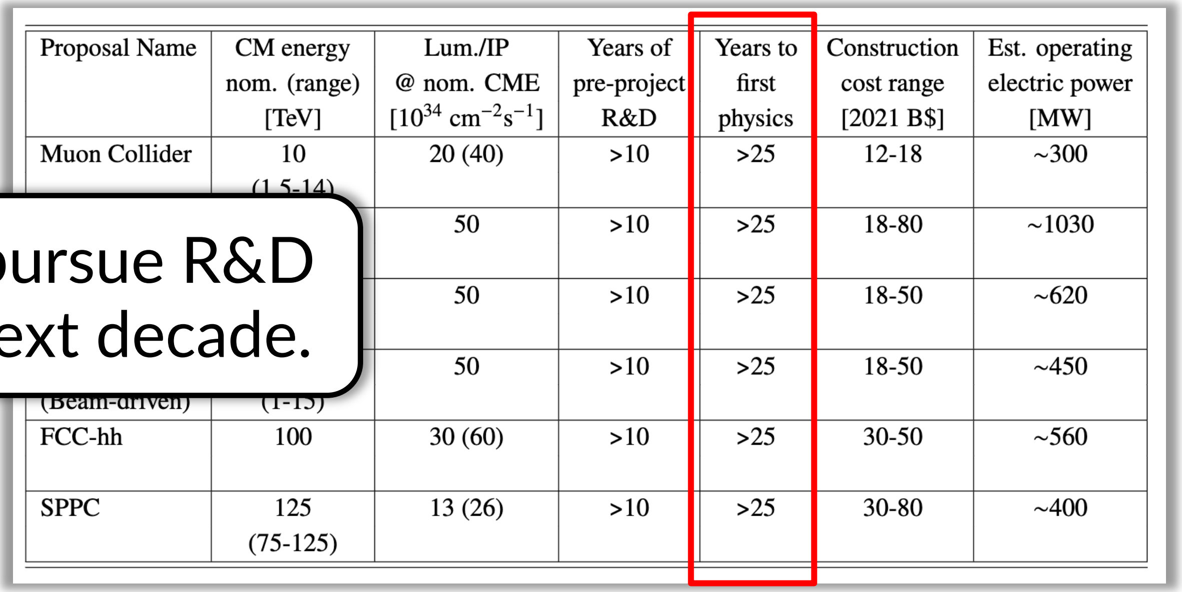

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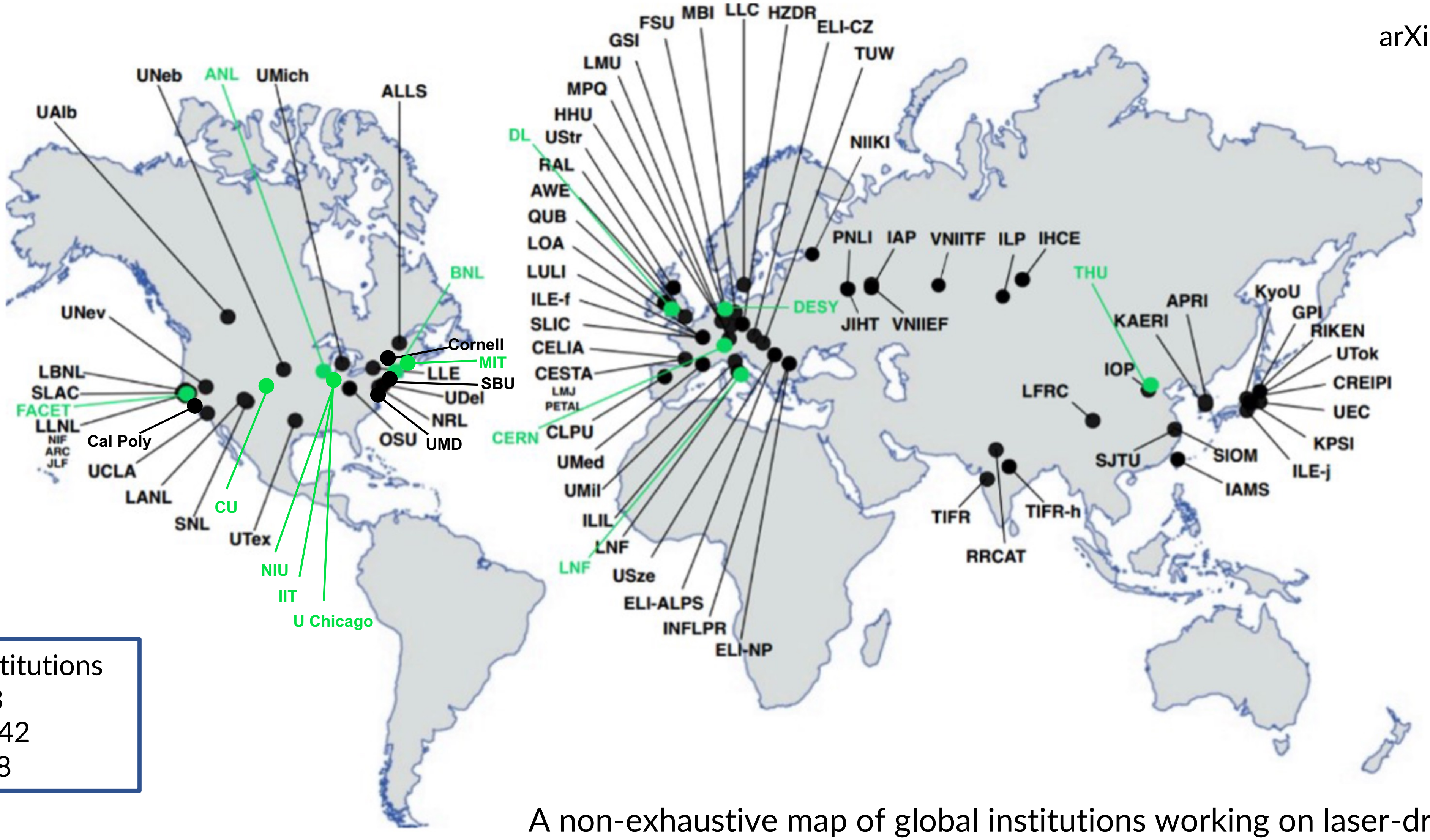
We must pursue R&D over the next decade.

Regardless of size, cost, and environmental impact, the Snowmass AF4 and ITF Frontiers concluded there are no near-term technologies for reaching 10 TeV parton-scale collisions.

Wakefield Accelerator Research is a Global Enterprise

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**).

arXiv:2203.11290

Wakefield Accelerator Research in the US

BELLA

FAST/IOTA

AWA

Stony Brook, Cornell, MIT, Maryland, Rochester

UCLA

Stanford, CU Boulder, Cal Poly, UC Irvine

ATF

FACET-II

ELL

UT^3

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

Universities with WFA programs

Large Beam Test Facilities
Universities
National Labs

arXiv:2203.11290

Wakefield Accelerator Research in the US

FAST/IOTA
Fermilab

AWA
Argonne NATIONAL LABORATORY

Stony Brook, Cornell, MIT, Maryland, Rochester

BELLA
BERKELEY LAB

ZEUS
M

UCLA

Universities conduct world-leading research and support DOE Laboratories.
DOE Laboratories provide training opportunities for students.

Stanford, CU Bo
Cal Poly, UC Irvine

ven
atory
ATF

FACET-II
SLAC NATIONAL ACCELERATOR LABORATORY

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

Large Beam Test Facilities
Universities
National Labs

Workforce Development

The Wakefield Accelerator Community addresses state-of-the-art challenges in accelerator physics, attracting young scientists who are looking to have an impact!

Our Beam Test Facilities provide unique opportunities for students to participate in groundbreaking accelerator R&D.

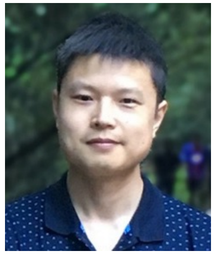
Support for Advanced Accelerator R&D is an investment in the Accelerator Physics workforce.

DOE Early Career Award


M. Turner
LBNL (2022)

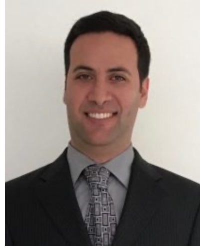

X. Lu
Argonne/NIU (2021)


B. O'Shea
SLAC (2020)


T. Zhou
LBNL (2020)


J. van Tilbourg
LBNL (2016)

NSF Early Career Award


N. Vafaei-Najafabadi
Stony Brook (2020)

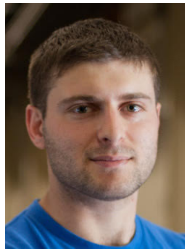

M. Litos
CU Boulder (2020)


F. Dollar
UC Irvine (2018)

APS DPB Thesis Prize


I. Lobach
Argonne (2022)

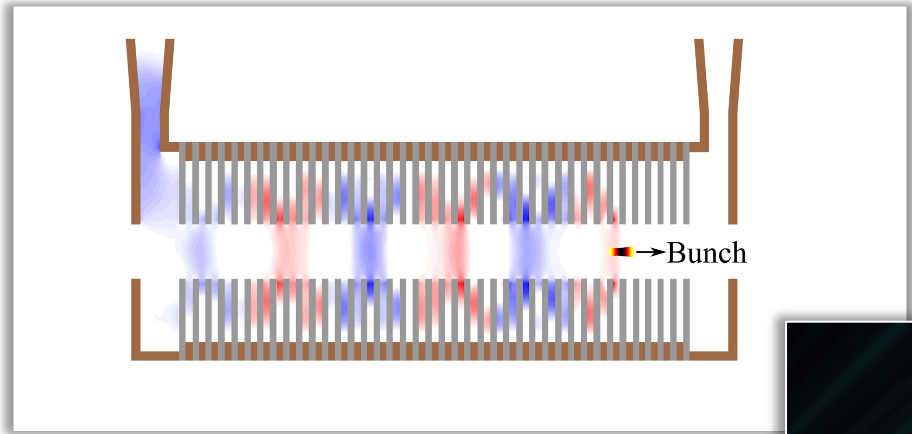

L. Obst-Heubl
LBNL (2021)


S. Gessner
SLAC (2017)


S. Corde
SLAC (2013)

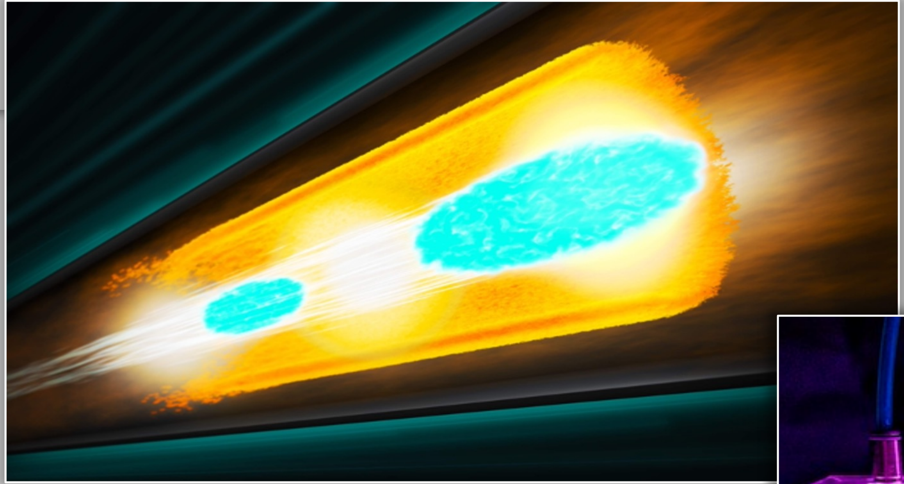
Wakefield Accelerator Technologies

Structure Wakefield Accelerators @

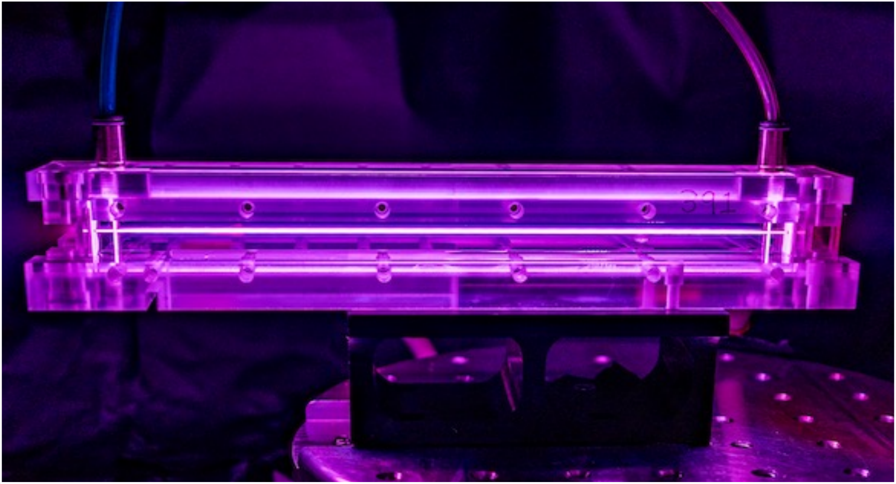


Argonne, SLAC, and LBNL are the stewards of SWFA, PWFA, and LWFA technology in the US, with university participation.

Beam Driven Plasma @ SLAC



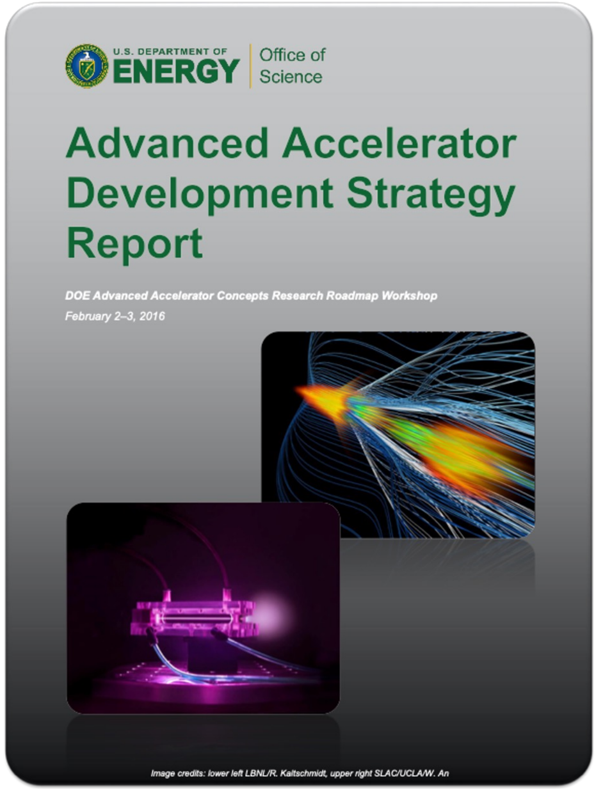
Laser Driven Plasma @ BERKELEY LAB



Key advantages:

Ultra-large gradients (1-100 GeV/m)
Ultra-short bunches (suppress beamstrahlung)

Wakefield Technologies Organized Around Common Goals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Advanced Accelerator Development Strategy Report

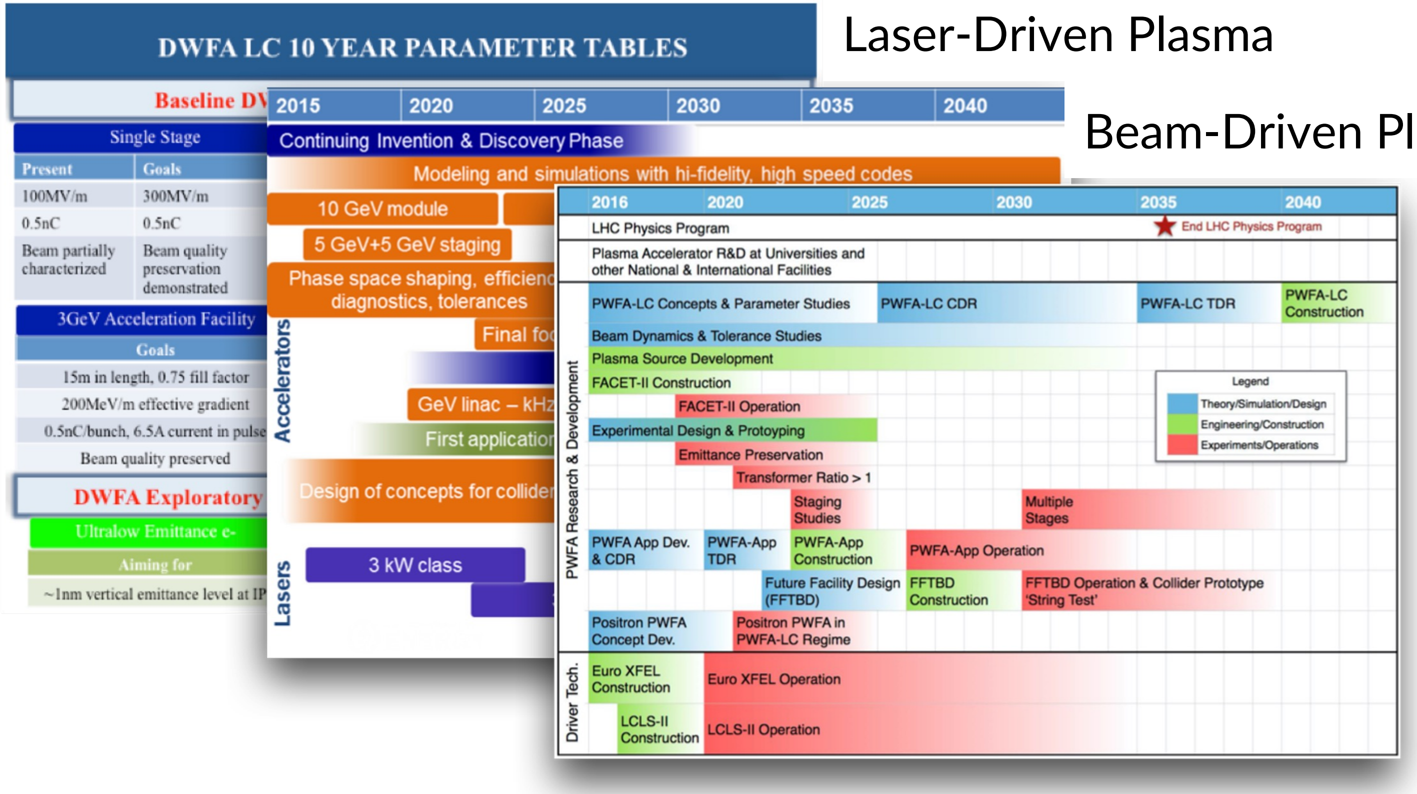
DOE Advanced Accelerator Concepts Research Roadmap Workshop
February 2–3, 2016

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

Structure Wakefield Acceleration

Laser-Driven Plasma

Beam-Driven Plasma



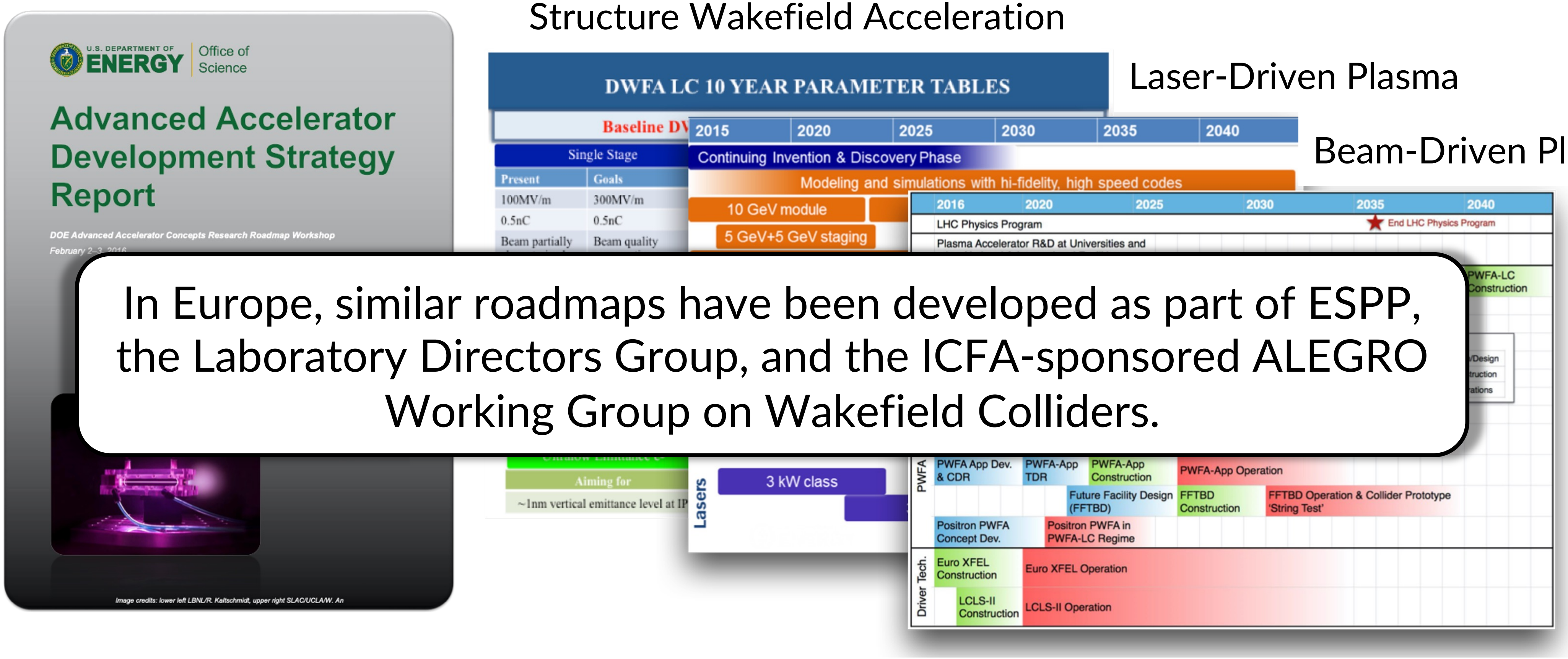
Roadmaps were developed in 2016 by the community in conjunction with DOE HEP following last P5 report and ensuing HEPAP Accelerator R&D sub-panel.

Wakefield Technologies Organized Around Common Goals

Structure Wakefield Acceleration

Laser-Driven Plasma

Beam-Driven Plasma



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DWFA LC 10 YEAR PARAMETER TABLES

Baseline DV
Single Stage

Present	Goals
100MV/m	300MV/m
0.5nC	0.5nC
Beam partially	Beam quality

Aiming for
~1nm vertical emittance level at IP

2015 | 2020 | 2025 | 2030 | 2035 | 2040
Continuing Invention & Discovery Phase
Modeling and simulations with hi-fidelity, high speed codes
10 GeV module
5 GeV+5 GeV staging
Lasers
3 kW class

2016 | 2020 | 2025 | 2030 | 2035 | 2040
LHC Physics Program
End LHC Physics Program
Plasma Accelerator R&D at Universities and
PWFA-LC Construction
PWFA: PWFA App Dev. & CDR; PWFA-App TDR; PWFA-App Construction; PWFA-App Operation
Future Facility Design (FFTBD); FFTBD Construction; FFTBD Operation & Collider Prototype 'String Test'
Positron PWFA Concept Dev.; Positron PWFA in PWFA-LC Regime
Driver Tech.: Euro XFEL Construction; Euro XFEL Operation
LCLS-II Construction; LCLS-II Operation

In Europe, similar roadmaps have been developed as part of ESPP, the Laboratory Directors Group, and the ICFA-sponsored ALEGRO Working Group on Wakefield Colliders.

Roadmaps were developed in 2016 by the community in conjunction with DOE HEP following last P5 report and ensuing HEPAP Accelerator R&D sub-panel.

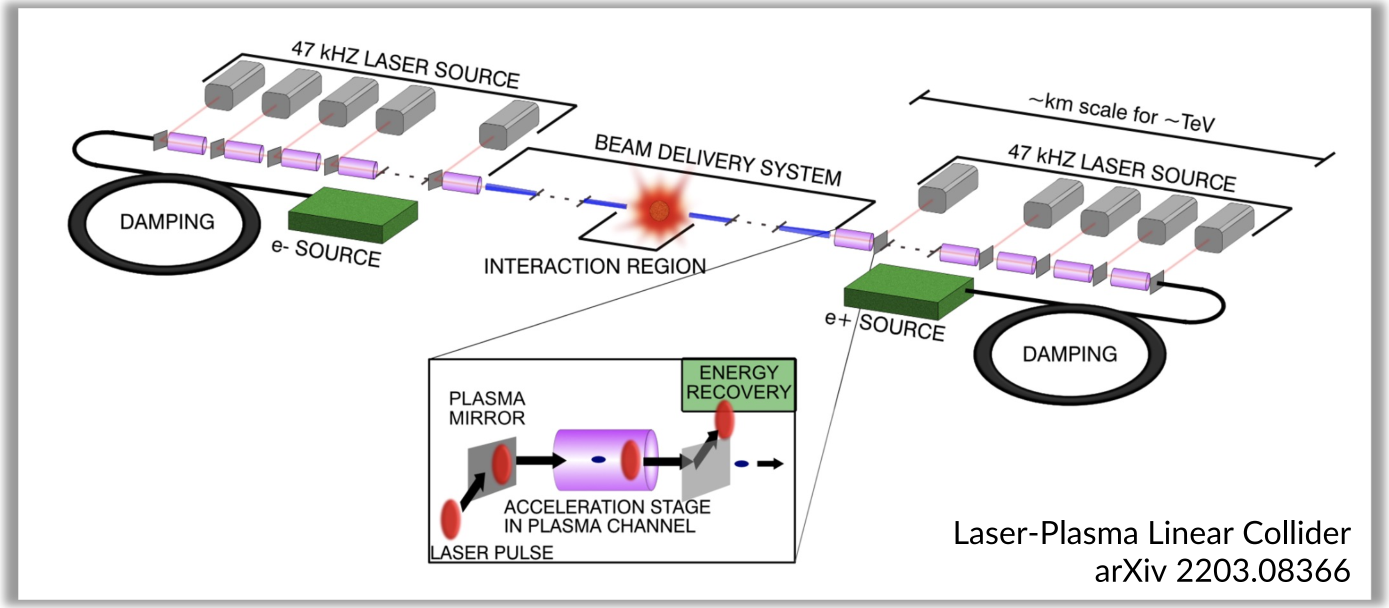
Progress Since Last P5

Goals

High-Gradient

High-Efficiency

Low-Emittance



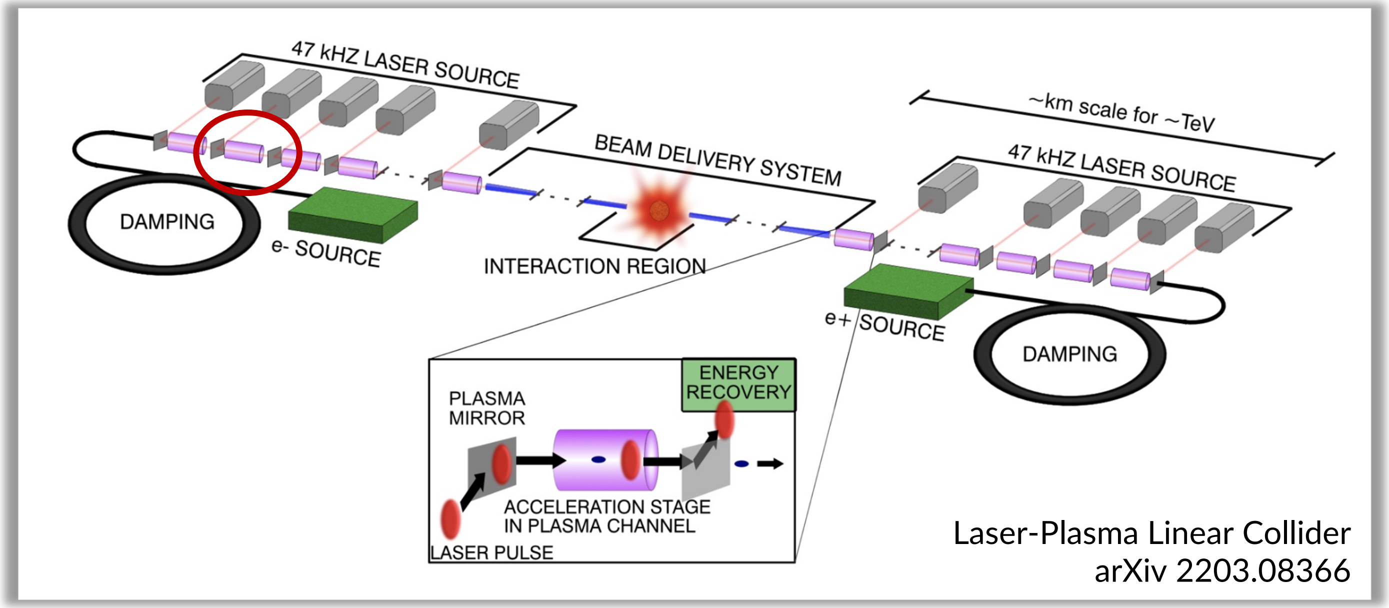
Laser-Plasma Linear Collider
arXiv 2203.08366

Progress Since Last P5

Excellent performance of single-stage accelerators

Goals

High-Gradient High-Efficiency Low-Emittance



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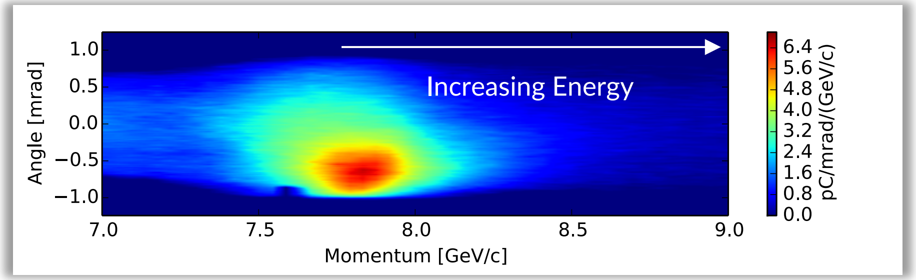
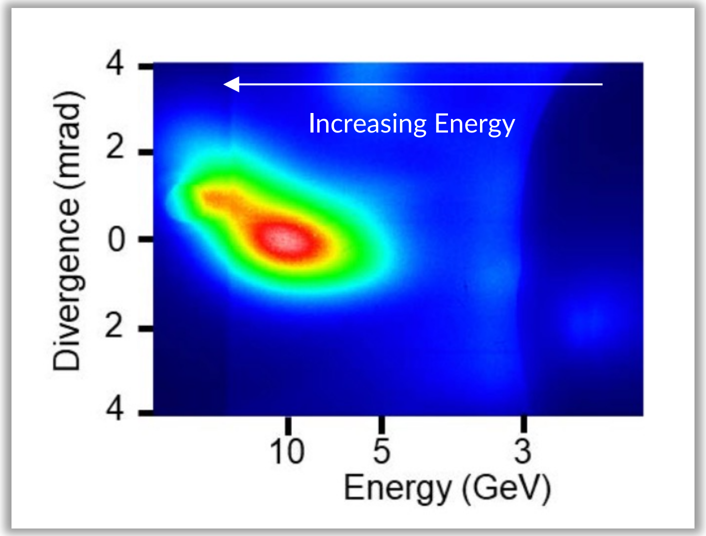
SLAC

Progress Since Last P5

Excellent performance of single-stage accelerators



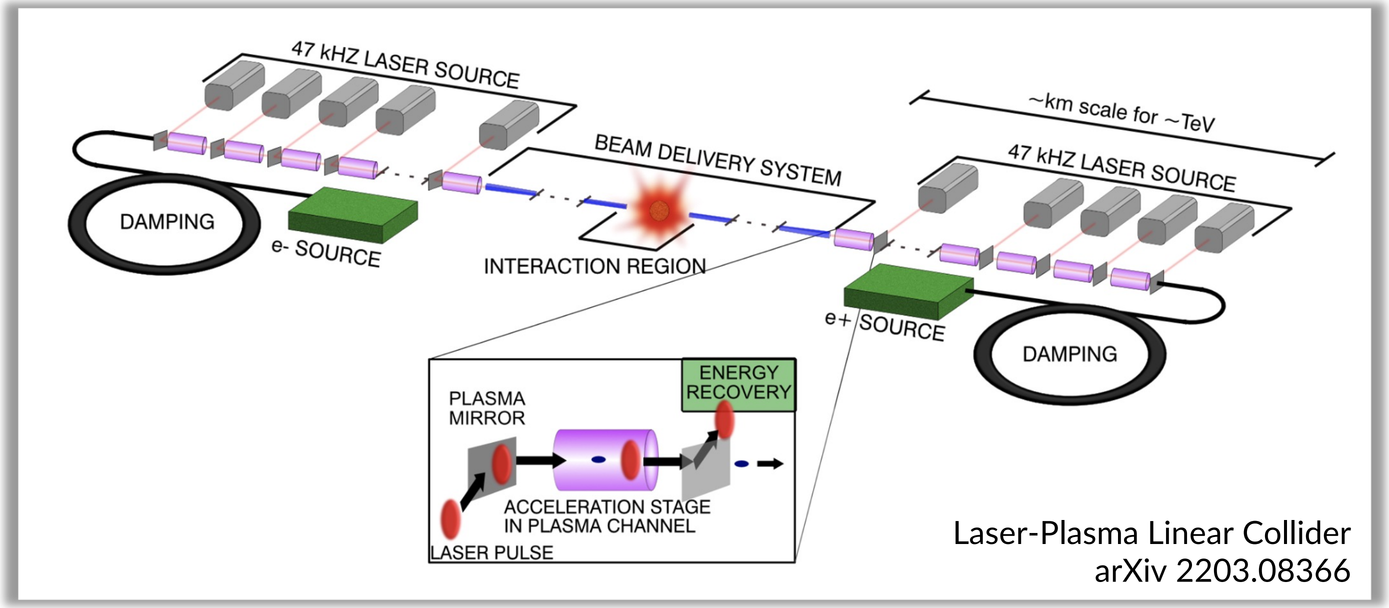
8 GeV Energy gain in LWFA
A. J. Gonsalves et al. PRL (2019)



10 GeV Energy gain in LWFA
C. Aniculaesei et al.
arXiv:2207.11492

Goals

High-Gradient High-Efficiency Low-Emittance



Laser-Plasma Linear Collider
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Progress Since Last P5

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Goals

High-Gradient

High-Efficiency

Low-Emittance

INSIGHT

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

FULL SPEED AHEAD

Plasma wakefield machines — the particle accelerators of the future? PAGES 40 & 92

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LIFE AFTER THE WALL
Science 25 years after the collapse of communism
PAGE 22

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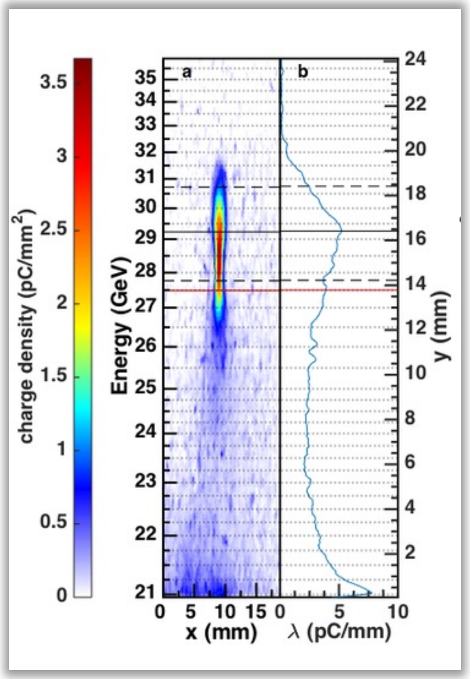
CASH, CONFLICT, CONSERVATION
To protect the planet, stop the infighting and fudging
PAGES 27, 28 & 32

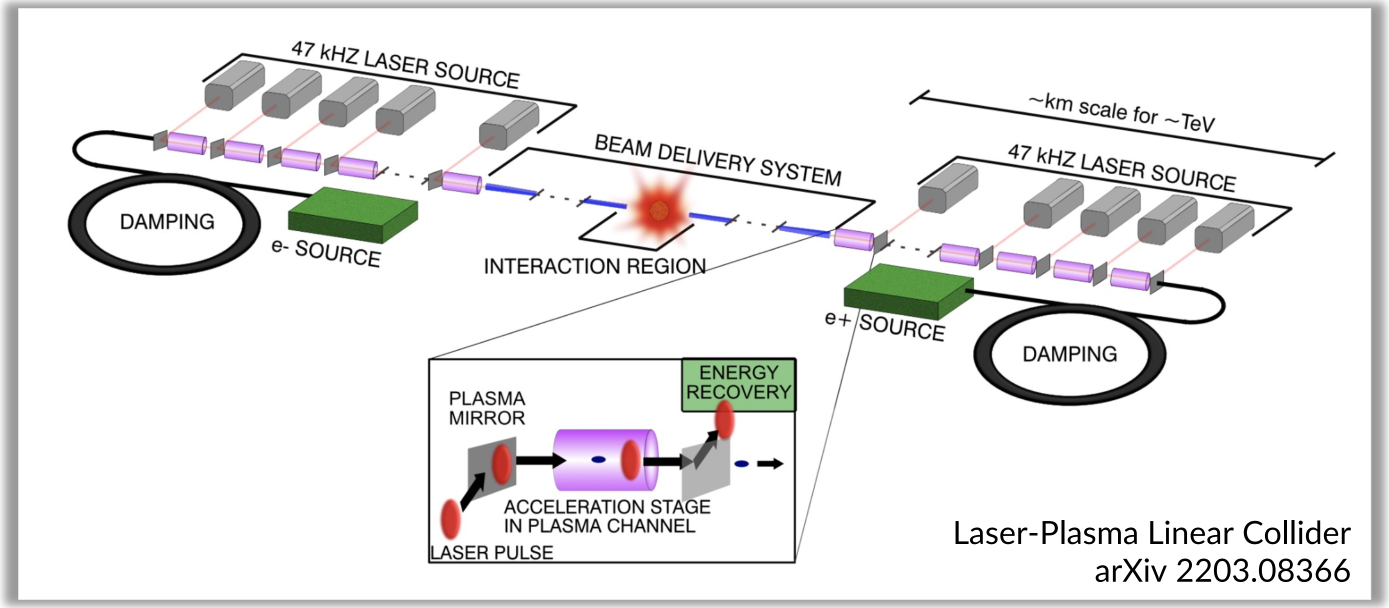
INTERACTIVE NOTEBOOKS
SHARE AND SHARE ALIKE
IPython allows on-the-run analysis
PAGE 151

NATURE.COM/NATURE

2 GeV Energy gain in PWFA
M. Litos et al. Nature (2014)



9 GeV Energy gain in PWFA
M. Litos et al. PPCF (2016)



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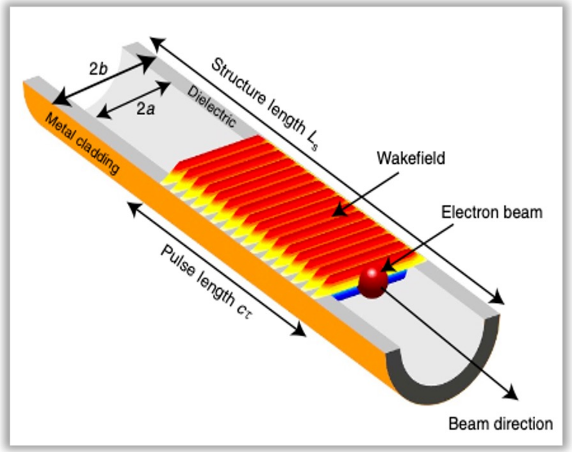
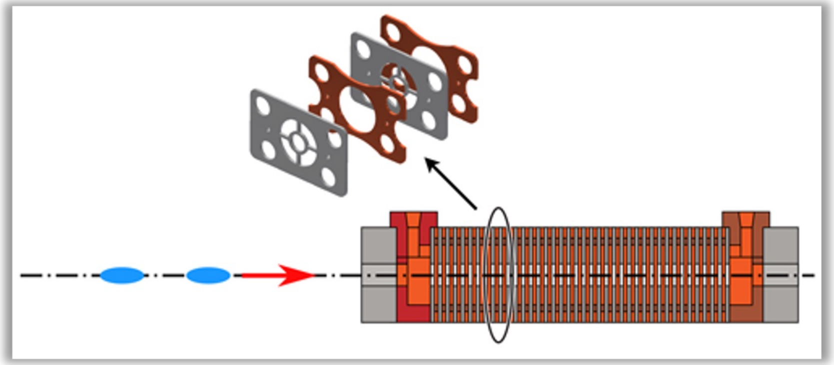


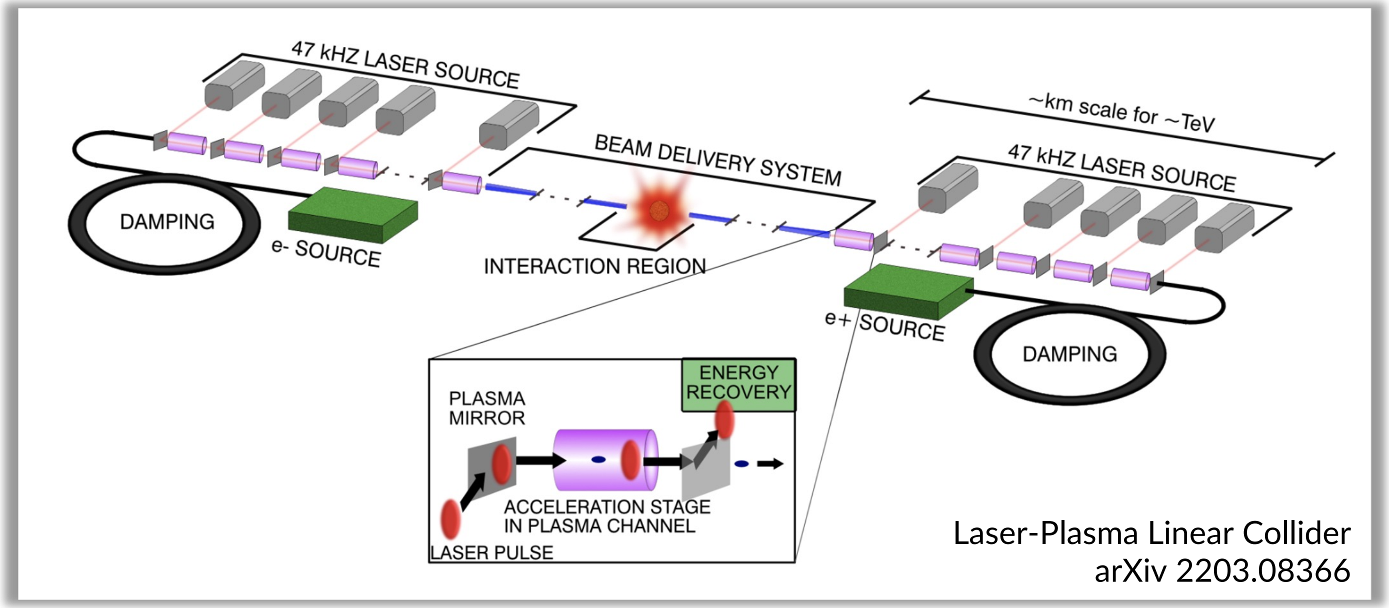
GV/m SWFA
B. O'Shea et al, Nat. Comm, (2016)



High-Power Metamaterial
X. Lu et al, PRL, (2019)

Goals

High-Gradient High-Efficiency Low-Emittance



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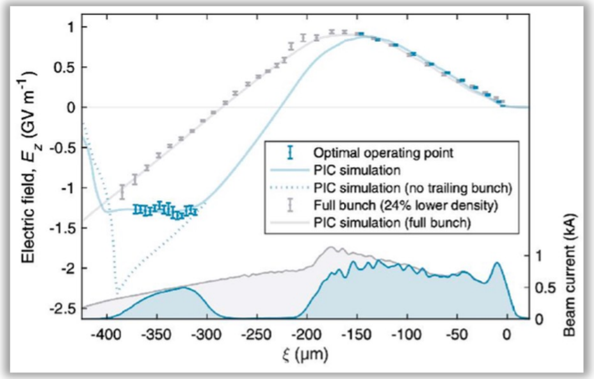


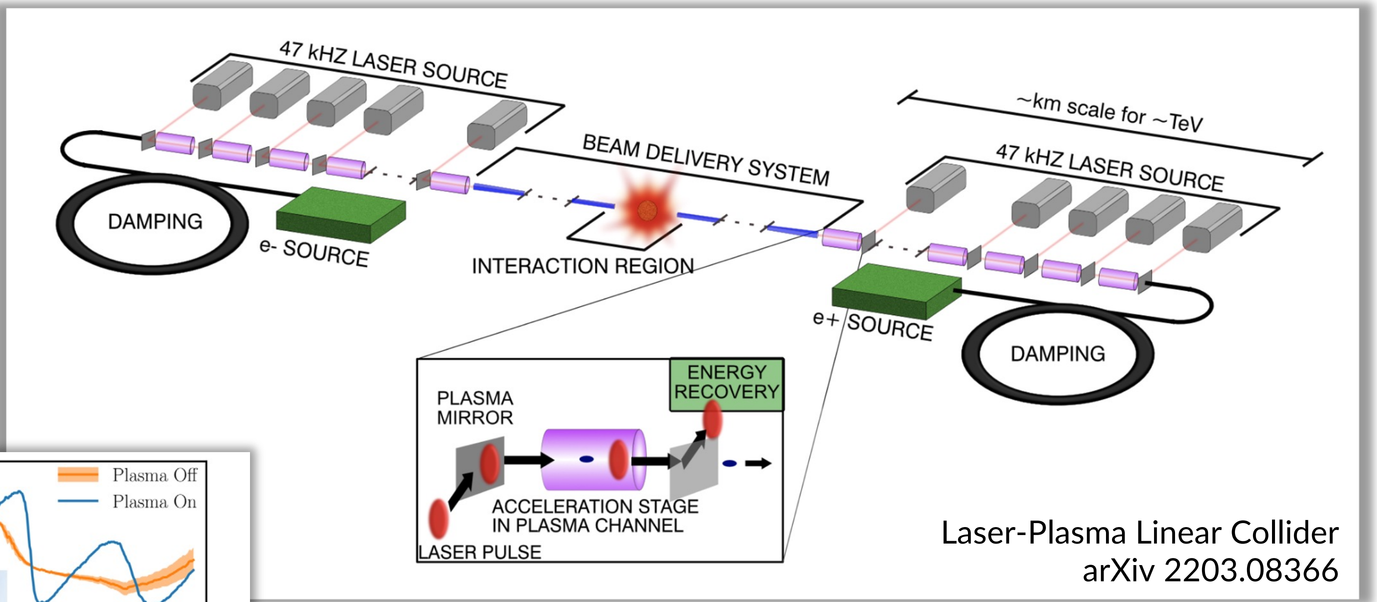
High-Efficiency, low energy spread
C. A. Lindstrom et al. PRL (2021)

Goals

High-Gradient

High-Efficiency

Low-Emittance



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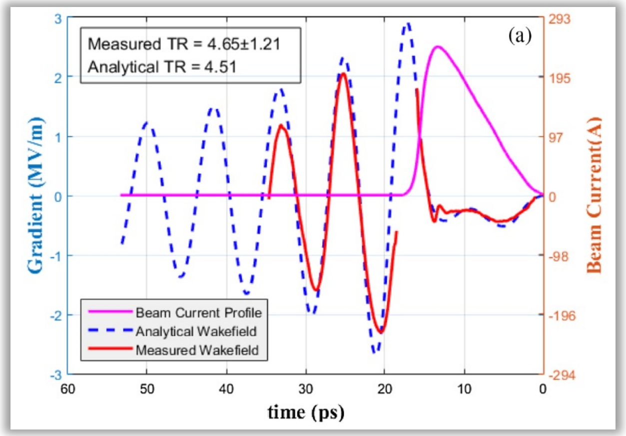
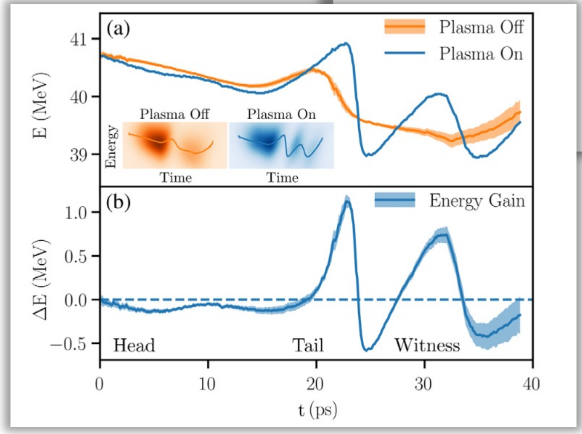


SWFA: Transformer Ratio = 5
Q. Gao et al. PRL (2018)



PWFA: Transformer Ratio = 8
R. Roussel et al. PRL (2020)

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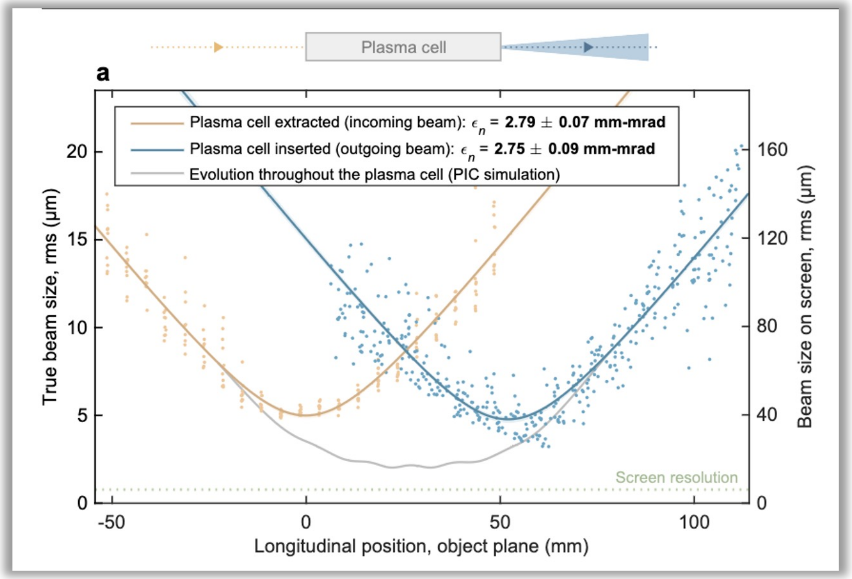
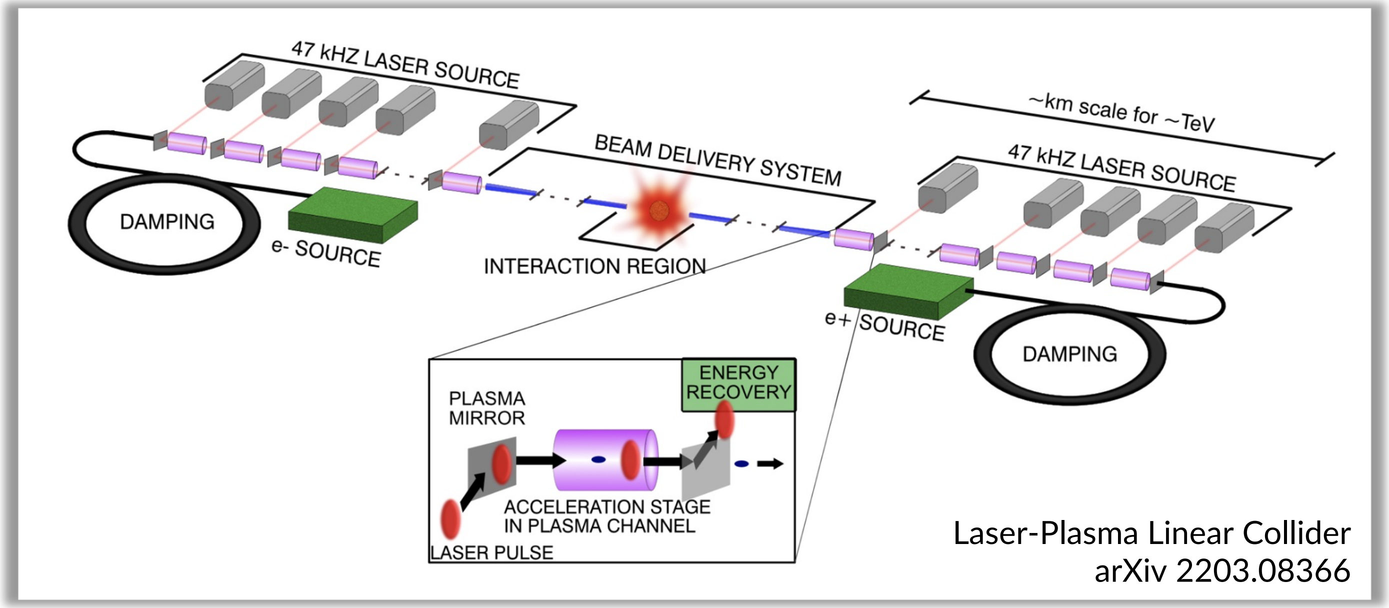
Goals

High-Gradient High-Efficiency Low-Emittance



Emittance Preservation
C. A. Lindstrom et al. (2022)
doi:10.21203/rs.3.rs-2300900/v1



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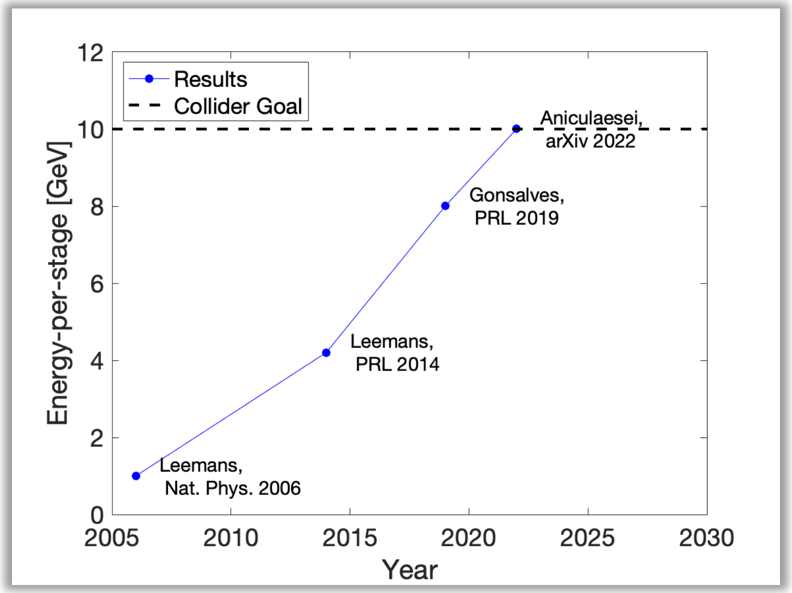
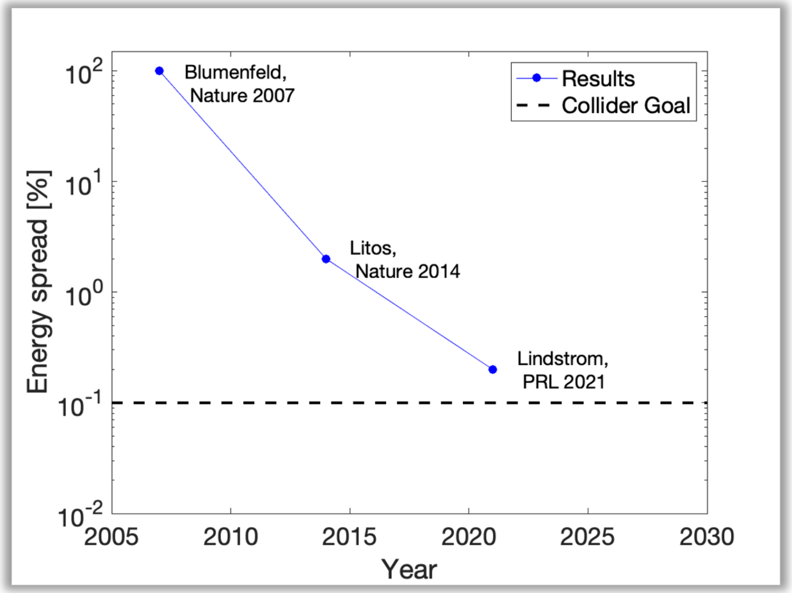
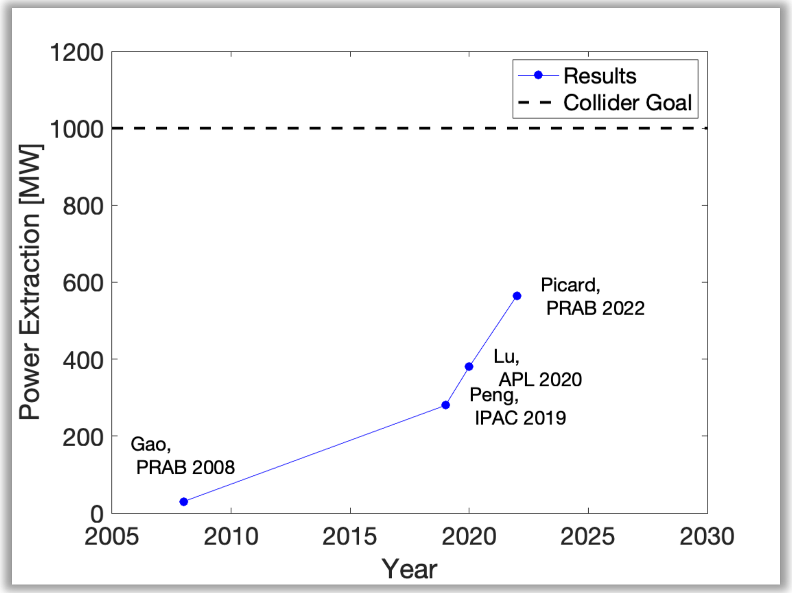
Laser-Driven Plasma



Beam-Driven Plasma



Structure Wakefield



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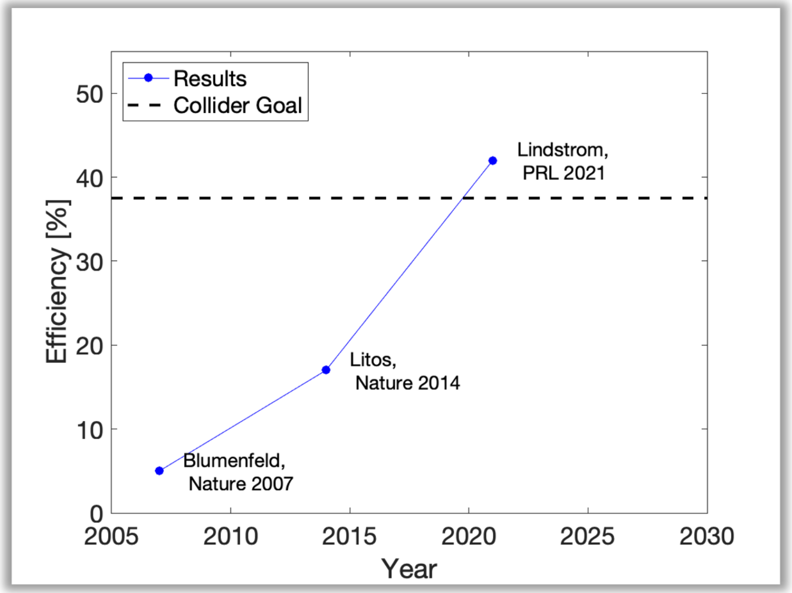

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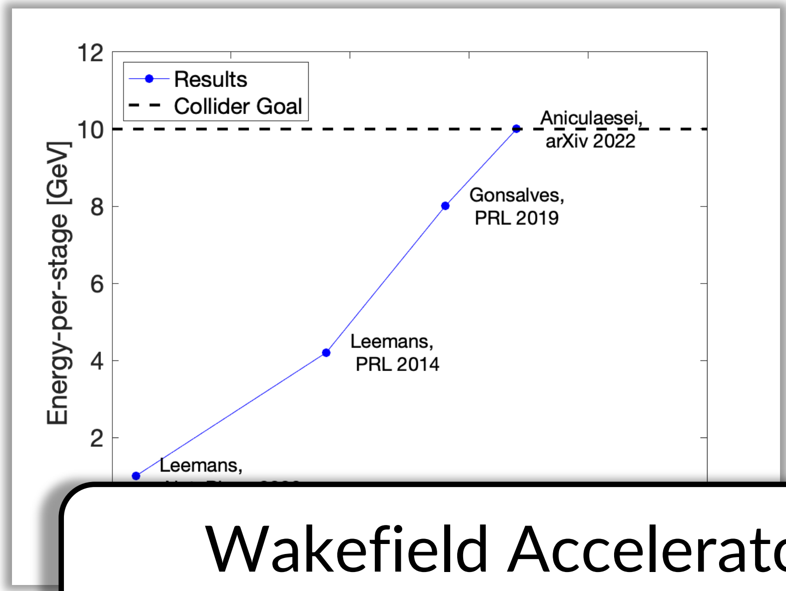
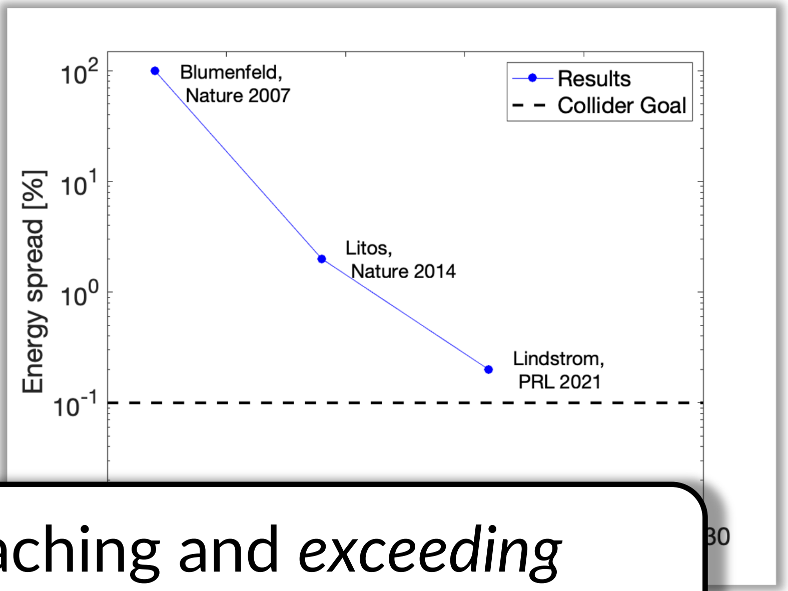
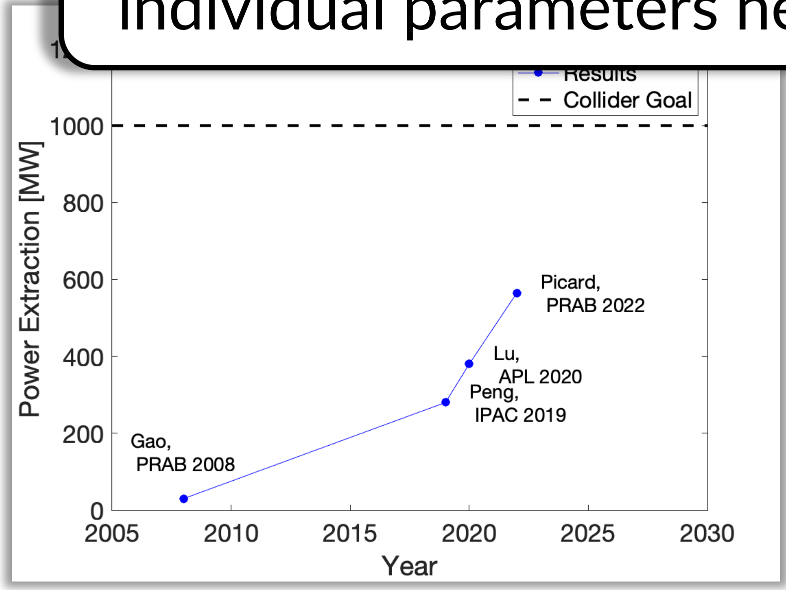


Beam-Driven Plasma

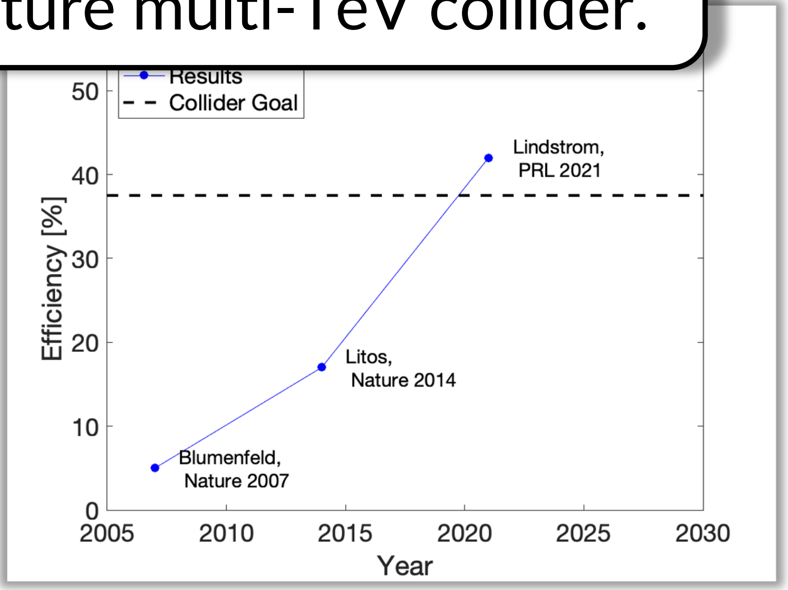


Wakefield Accelerators are approaching and *exceeding* individual parameters needed for a future multi-TeV collider.

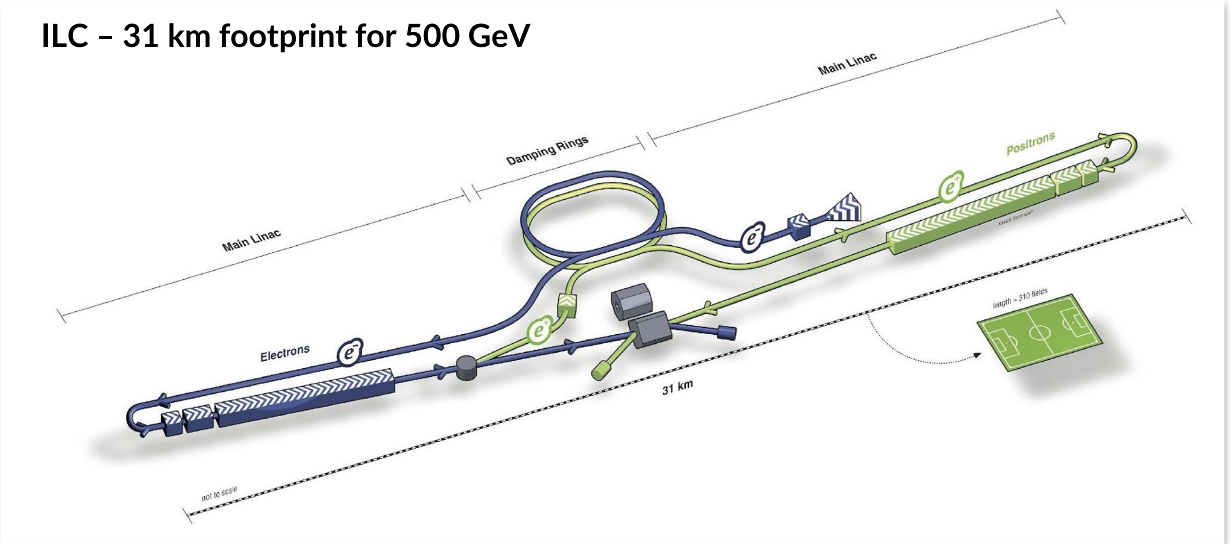
Structure Wakefield

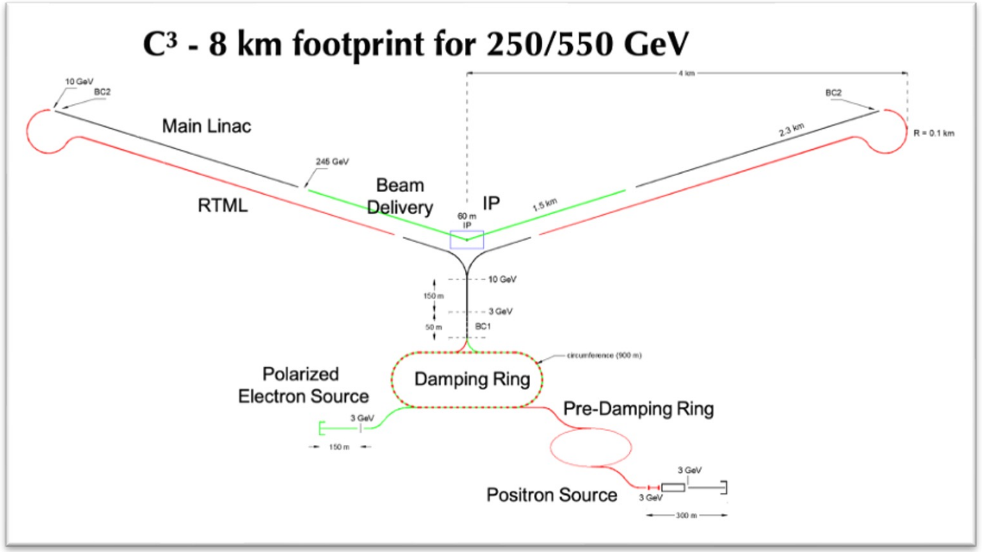


Beam-Driven Plasma



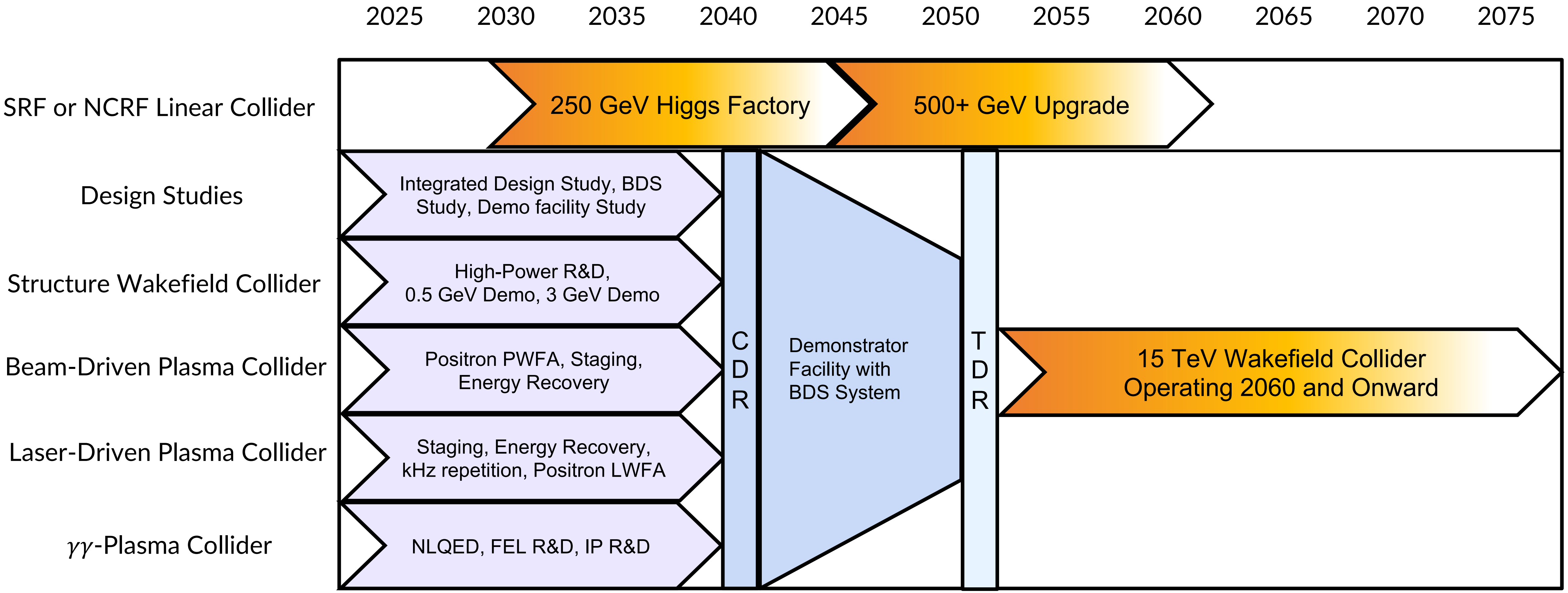
The Path to 10 TeV and Beyond





A 10 TeV-scale Wakefield Collider could extend the energy reach of a Linear Collider Higgs Factory based on SRF or NCRF technology.

The Path to 10+ TeV



2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075

SRF or NCRF Linear Collider

250 GeV Higgs Factory

500+ GeV Upgrade

Design Studies

Integrated Design Study, BDS Study, Demo facility Study

Structure Wakefield Collider

High-Power R&D, 0.5 GeV Demo, 3 GeV Demo

Beam-Driven Plasma Collider

Positron PWFA, Staging, Energy Recovery

Laser-Driven Plasma Collider

Staging, Energy Recovery, kHz repetition, Positron LWFA

$\gamma\gamma$-Plasma Collider

NLQED, FEL R&D, IP R&D

CDR

Demonstrator Facility with BDS System

TDR

15 TeV Wakefield Collider Operating 2060 and Onward

Wakefield Accelerators can be developed in parallel with the operation of Linear Collider Higgs Factories to provide a staged upgrade path to the energy frontier.

The Next Steps

Challenges

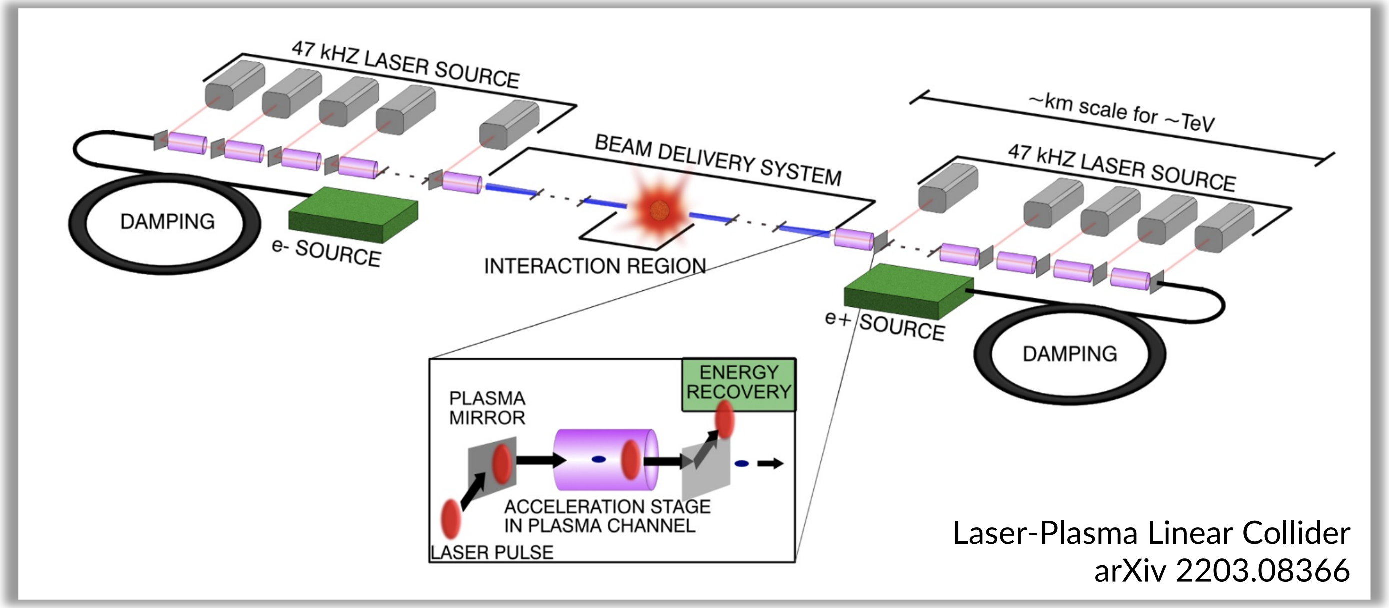
Staging

Repetition Rate

Positron Acc.

Energy Recovery

Beam Delivery Syst.



Laser-Plasma Linear Collider
arXiv 2203.08366

Some of the next steps in the R&D path are achievable at existing facilities, while others are not.

The Next Steps

Challenges

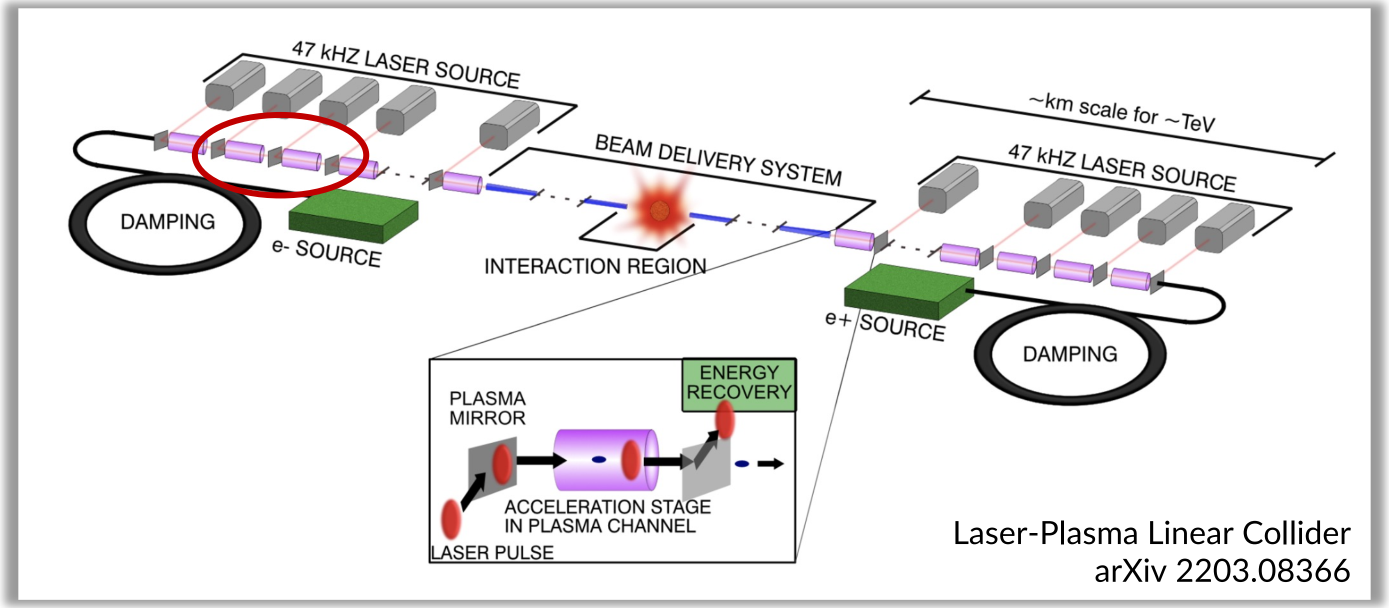
Staging

Repetition Rate

Positron Acc.

Energy Recovery

Beam Delivery Syst.



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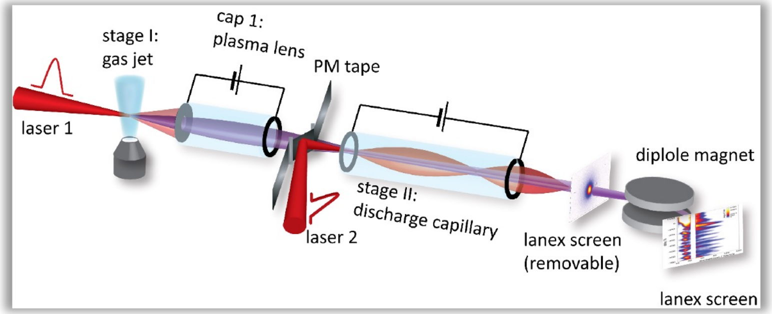
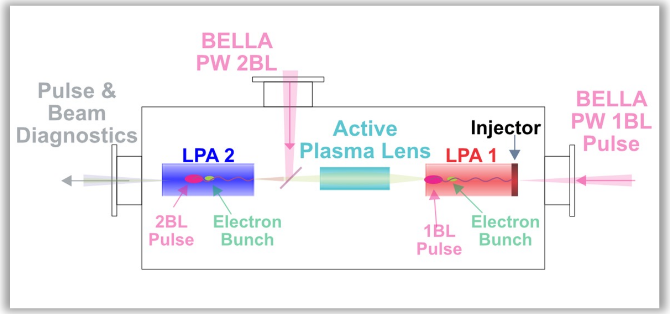
The Next Steps: Staging

A proof-of-principle demonstration of staging was performed at LBNL in 2016.

BELLA is well-positioned to demonstrate GeV-scale staging with the existing facility.



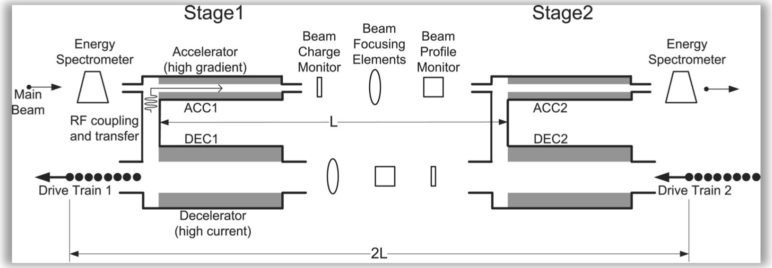
100 MeV-scale of LWFA Accelerators
S. Steinke et al. Nature (2016)



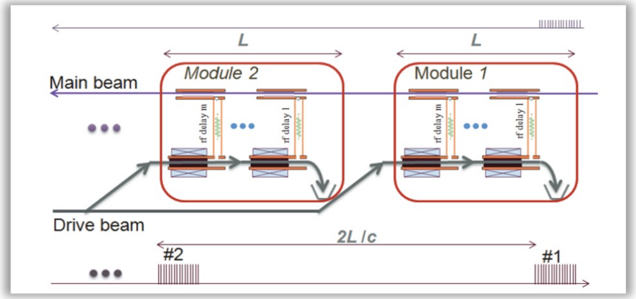
GeV-scale staging schematic

AWA plans a 0.5-GeV demo followed by a 3-GeV fully-featured module.

Ask to P5: Upgrade AWA facility for 0.5 GeV demonstrator.



SWFA Staging Experiment
C. Jing et al NIM A (2018)

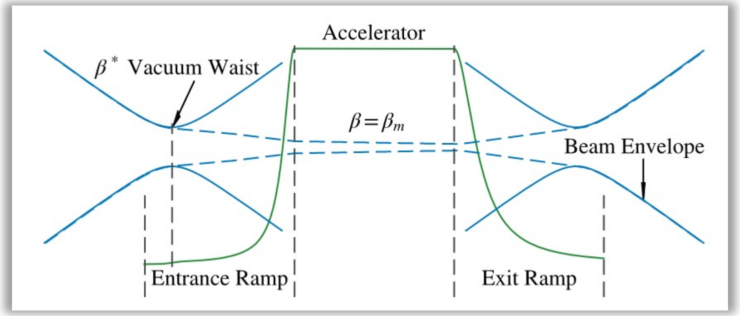


SWFA 0.5 GeV Staging Demo
C. Jing and G. Ha, JINST (2022)

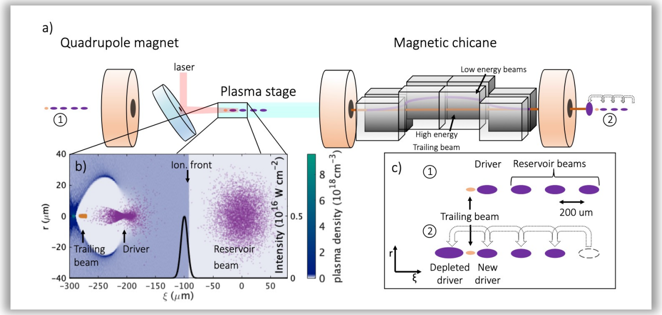
FACET-II can study beam transport in and out of a single stage.

Future Request: Facility for demonstrating two or more PWFA stages.

Note to P5: PWFA Staging experiment may be possible at C^3 Demo facility.



Beam matching with plasma ramps
R. Ariniello et al. PRAB (2019)



Laser-gated multistage plasma accelerator
A. Knetsch et al. arXiv:2210.02263

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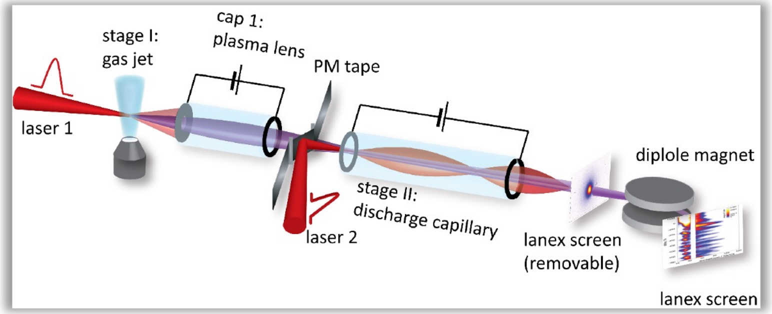

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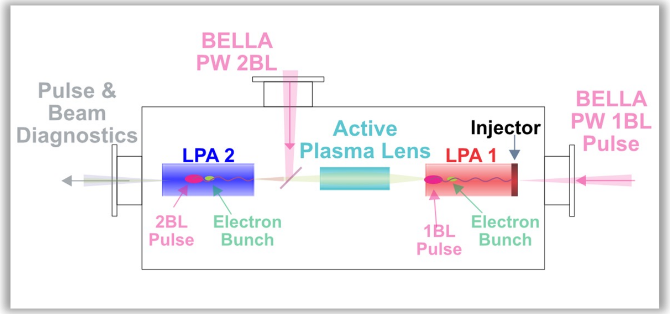

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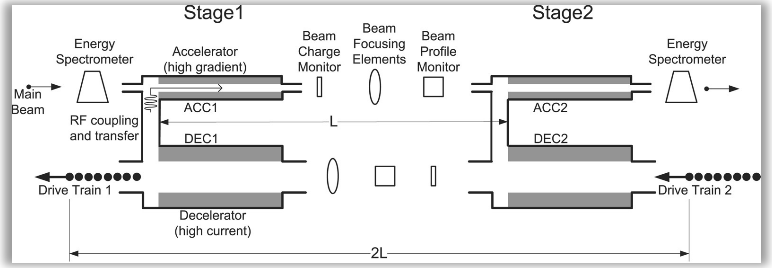

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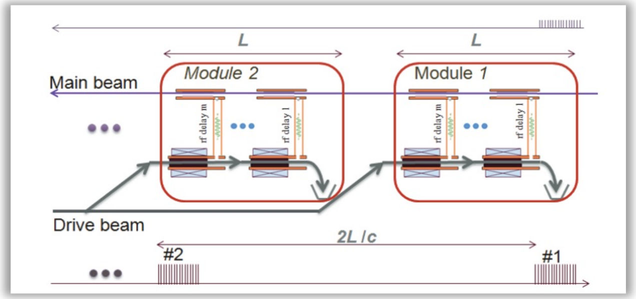

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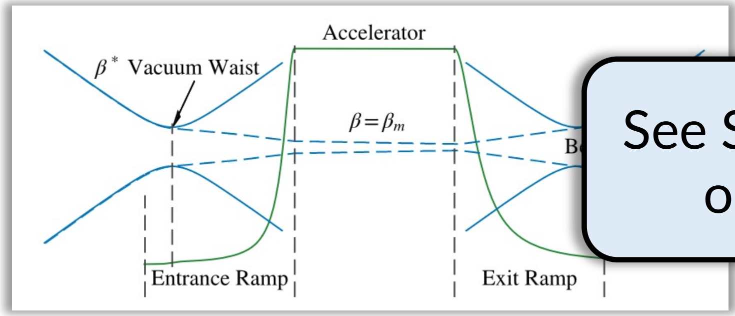

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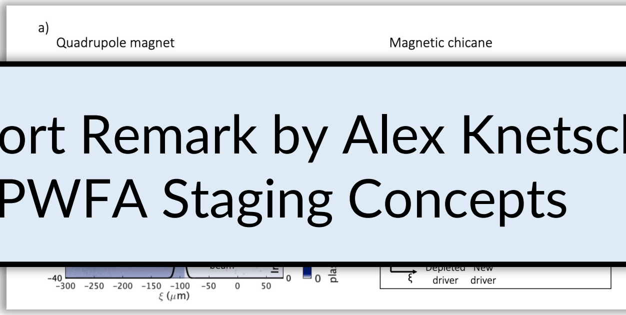


See Short Remark by Alex Knetsch on PWFA Staging Concepts

Laser-gated multistage plasma accelerator
A. Knetsch et al. arXiv:2210.02263

The Next Steps

Challenges

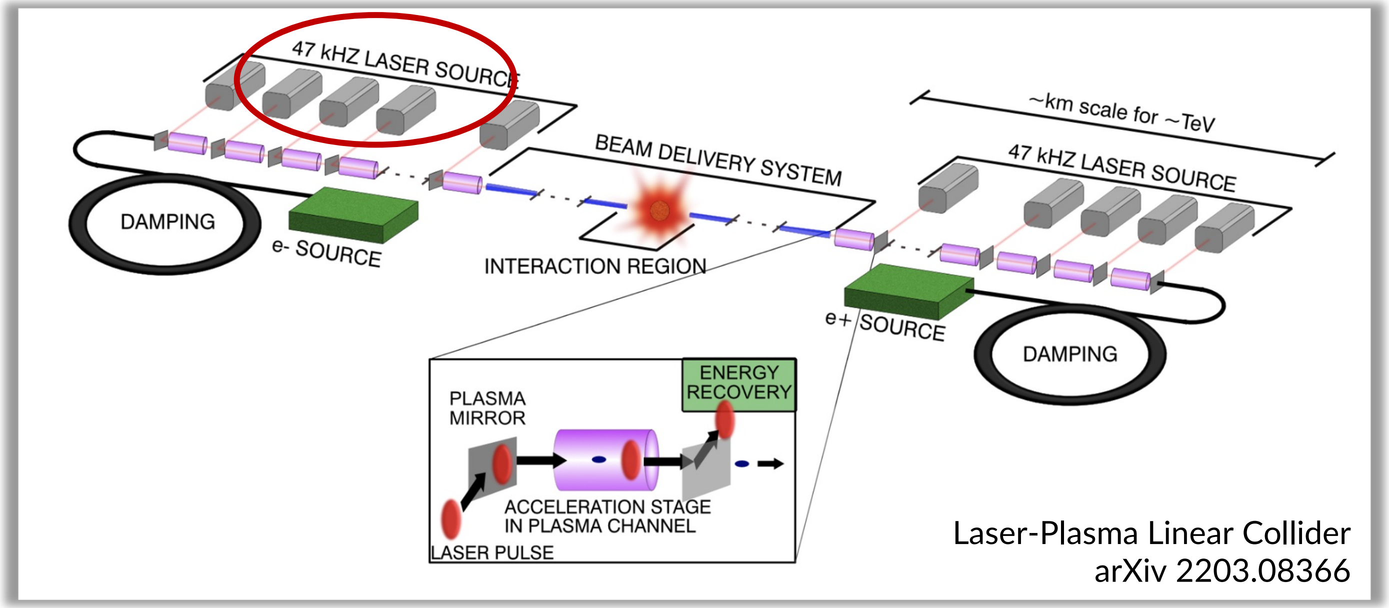
Staging

Repetition Rate

Positron Acc.

Energy Recovery

Beam Delivery Syst.



Laser-Plasma Linear Collider
arXiv 2203.08366

The Next Steps: Repetition Rate

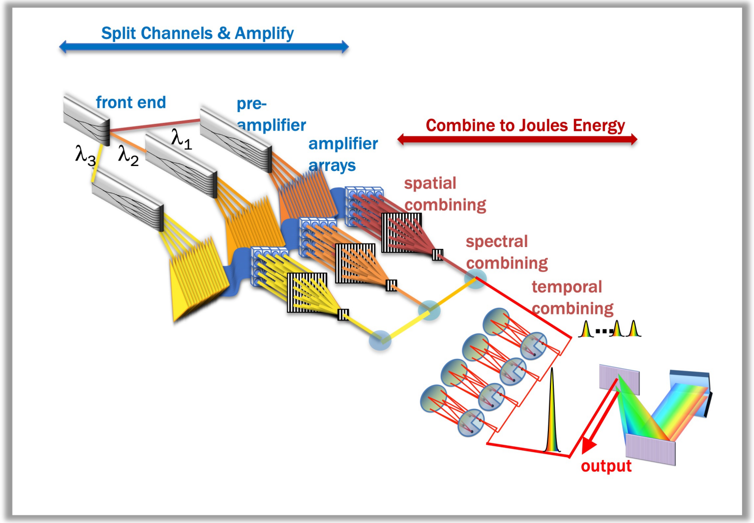
kHz-class lasers require new technology, such as fiber-combined lasers. kBELLA will:

- Demonstrate efficient driver for LWFA
- Demonstrate active feedback for precision LWFA.
- Enable kHz rep-rate applications.
- Address the cost of driver technology.
- High-rep rate operation also provides valuable information for beam-driven plasma accelerators.
- Basis for a user facility.

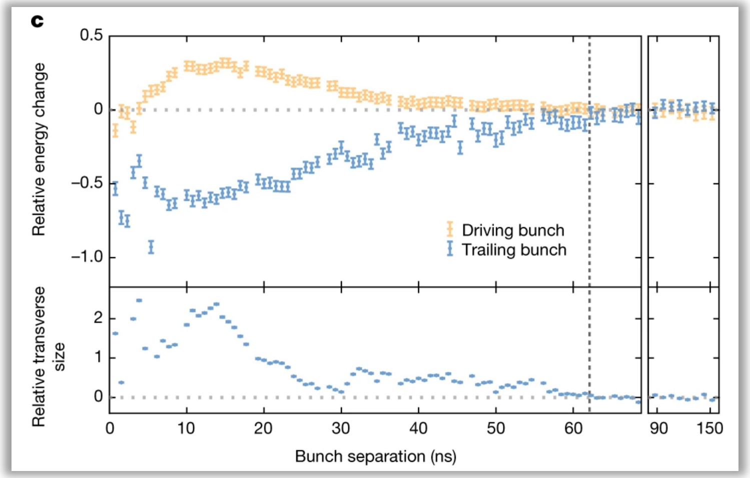
Ask to P5: Support for kBELLA upgrade to demonstrate LWFA with kHz-class lasers.

Fast plasma recovery time was demonstrated at FLASHForward at DESY.

FLASHForward is well-positioned to study MHz-scale repetition rates with beam-driven plasma accelerators.



Fiber-combination of lasers
T. Zhou ECA 2020



Fast Recovery Time
R. D'Arcy et al. Nature (2022)

The Next Steps

Challenges

Staging

Repetition Rate

Positron Acc.

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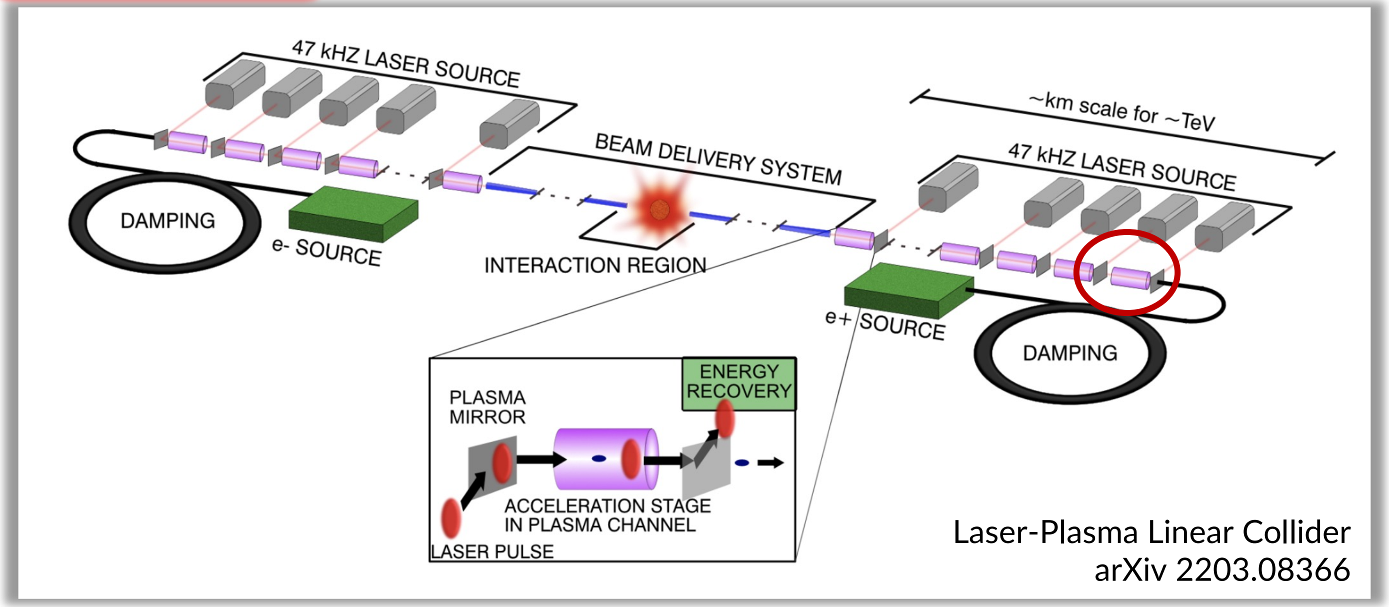
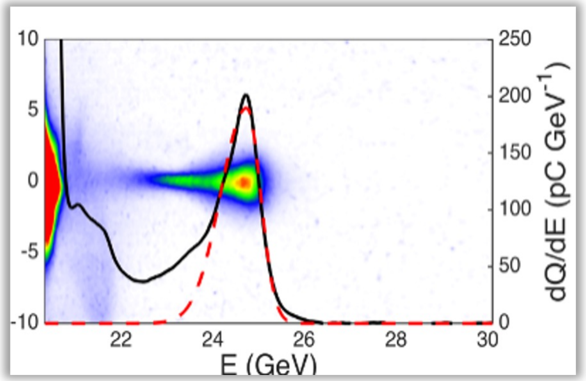


Laser-Plasma Linear Collider
arXiv 2203.08366

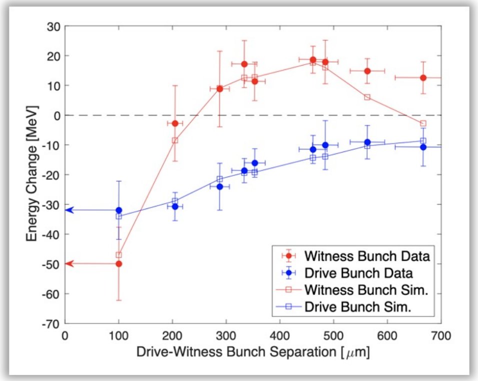
The Next Steps: Positron Acceleration

Major advances at FACET (2014-2016) on our understanding of positron acceleration in plasma.

SLAC is the only lab that pursues positron PWFA research, leveraging SLC infrastructure.

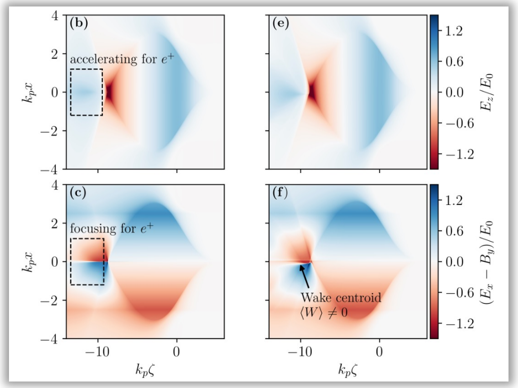


S. Corde et al, Nature (2015)



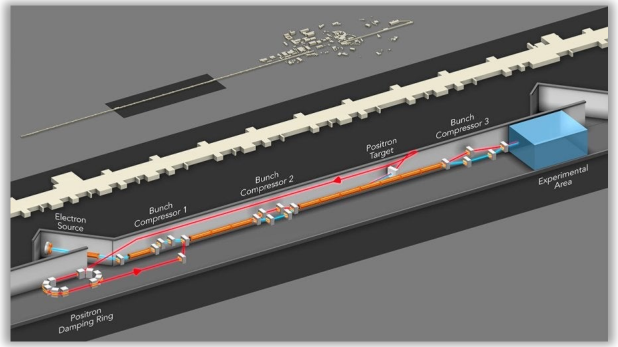
S. Gessner et al, arXiv:2304.01700

Research at FACET inspired novel ideas for high-quality, stable acceleration of positrons in plasma.



S. Diederichs et al, Phys. Rev. Acc. Beams (2022)

Ask to P5: Support for the FACET-II Positron Upgrade to demonstrate high-quality acceleration of positrons in plasma.



See DESY Letter of Support for Positrons at FACET-II at end of talk.

The Next Steps

Challenges

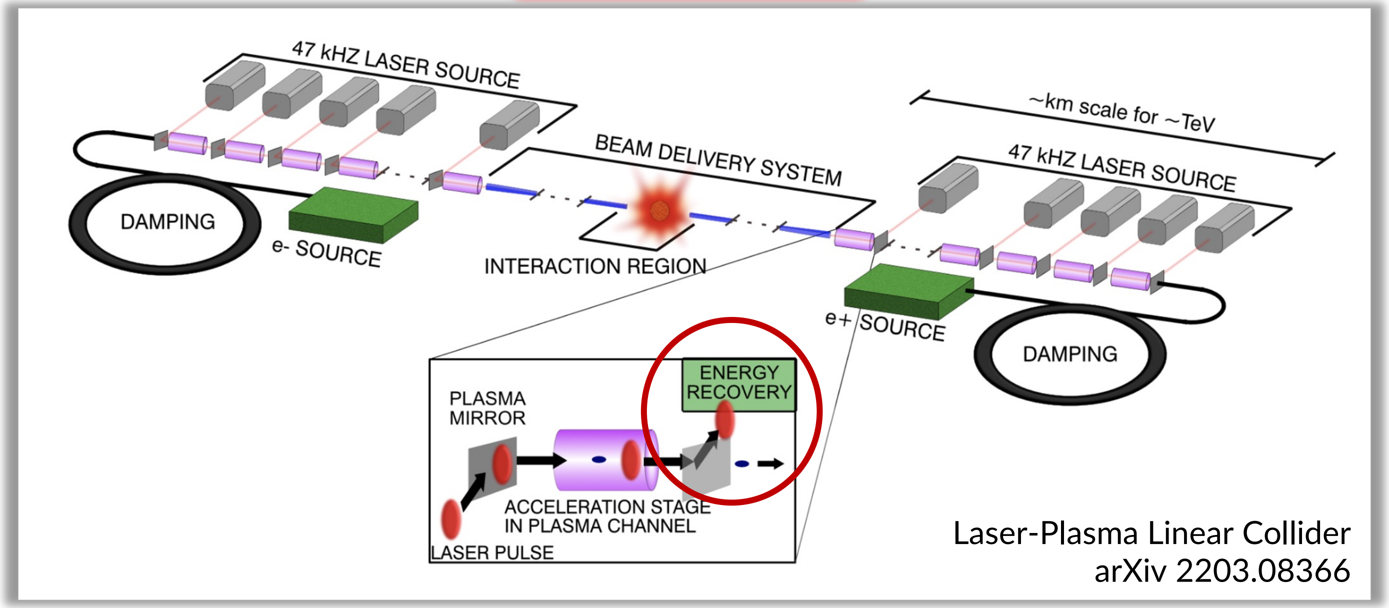
Staging

Repetition Rate

Positron Acc.

Energy Recovery

Beam Delivery Syst.



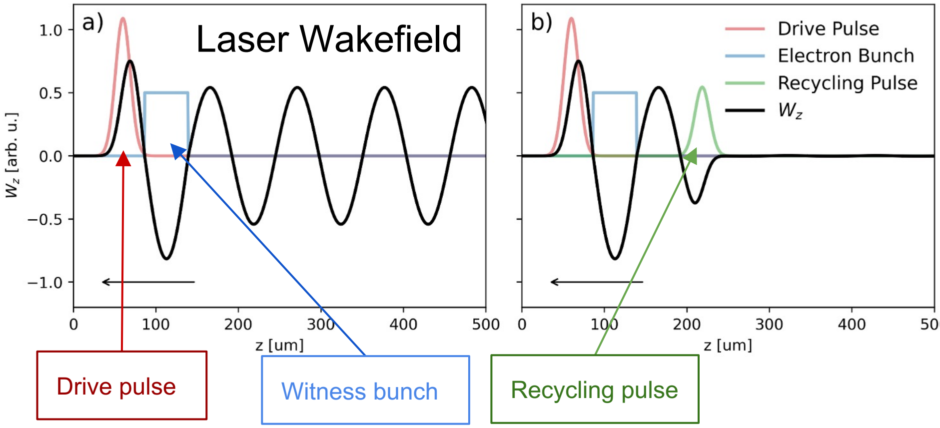
Laser-Plasma Linear Collider
arXiv 2203.08366

The Next Steps: Energy Recovery

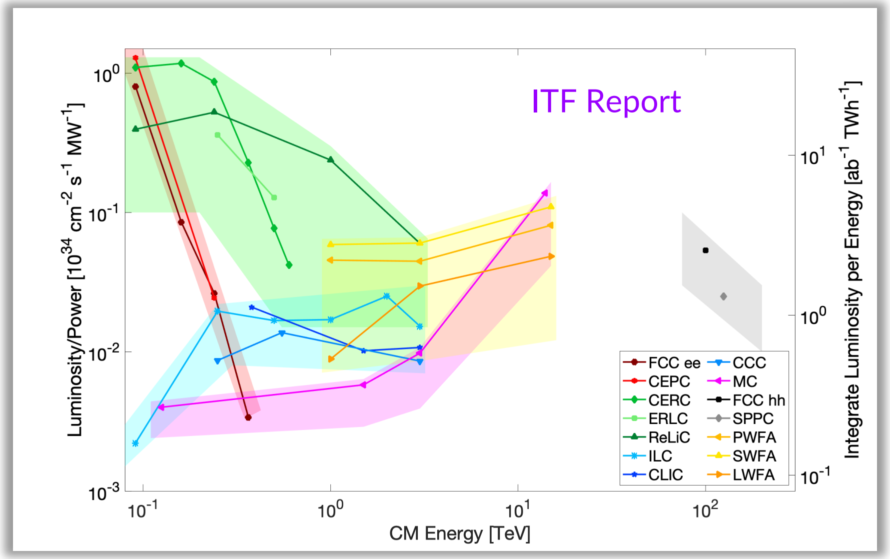
Energy recovery is a critical technology for laser-driven plasma accelerators and positron acceleration in plasma.

Energy recovery maximizes the possible luminosity while minimizing the carbon footprint of the collider.

BELLA is well-positioned to address energy recovery R&D.



M. Turner, LBNL, Early Career Award
Energy Recycling for Green Plasma-Based Collider



The Next Steps

Challenges

Staging

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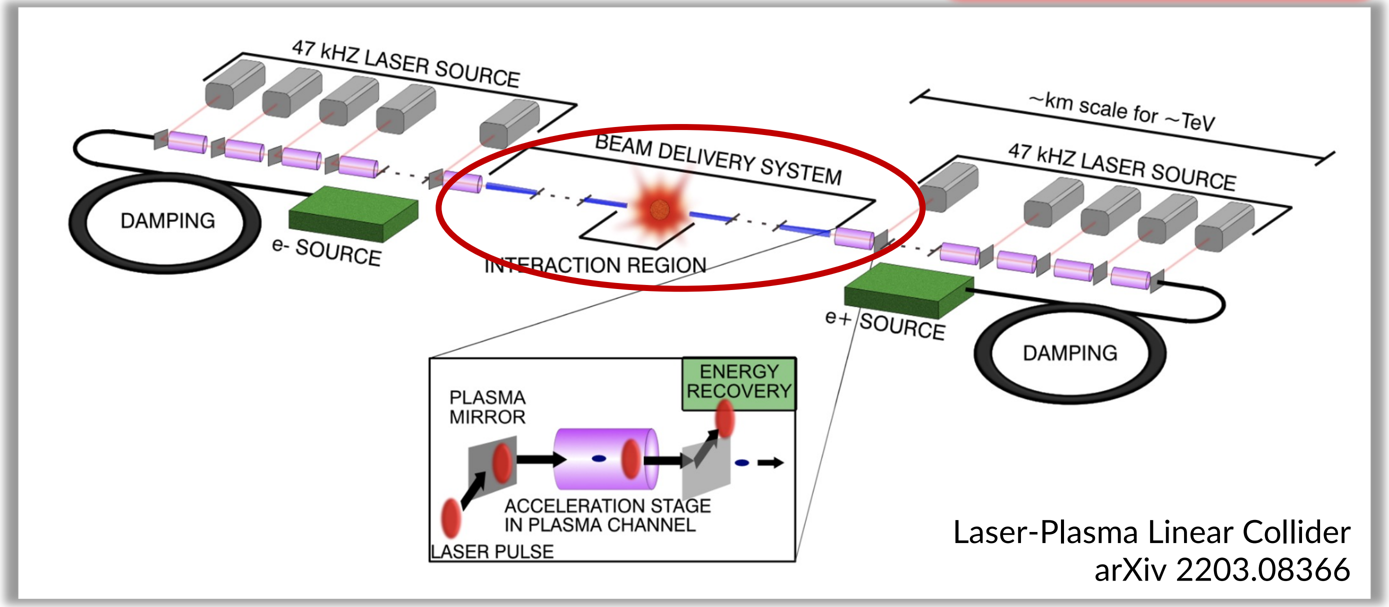


Laser-Plasma Linear Collider
arXiv 2203.08366

The Next Steps: Beam Delivery System

The scaling of Beam Delivery Systems to ultra-high energy is a unique challenge.

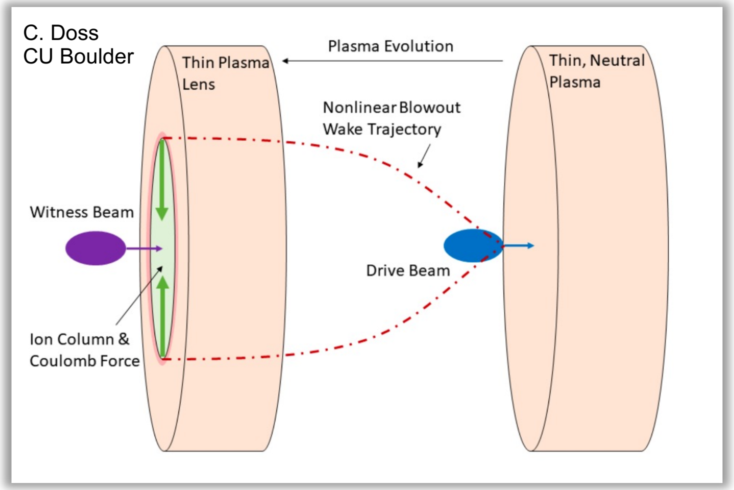
FACET-II and BELLA have research programs that address plasma lenses for compact BDS.

Beamstrahlung effects must be addressed and understood in the multi-TeV regime.

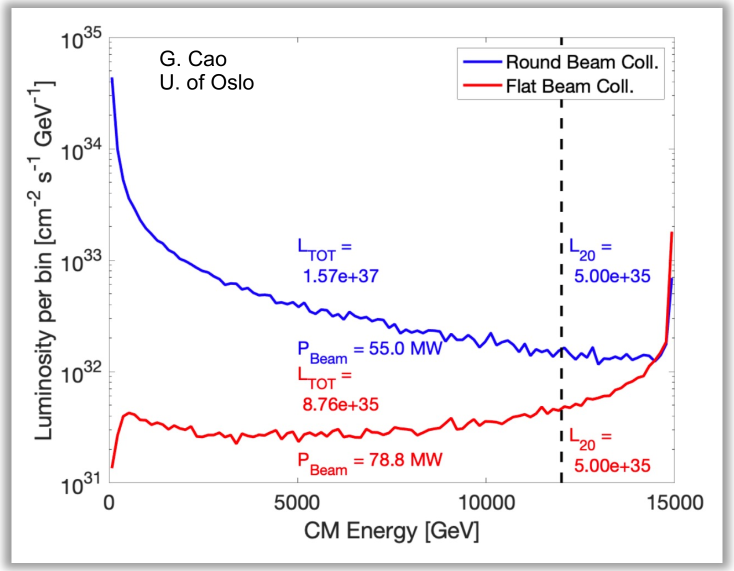
We have formed a new collaboration to use state-of-the-art Particle-in-Cell codes to examine beamstrahlung at ultra high energy (arXiv:2305.00573).

Ask to P5: Support for multi-TeV beamstrahlung studies from the newly-formed National Collider R&D initiative.

Plasma Lens for Compact Focus



Luminosity Spectrum at Large Υ



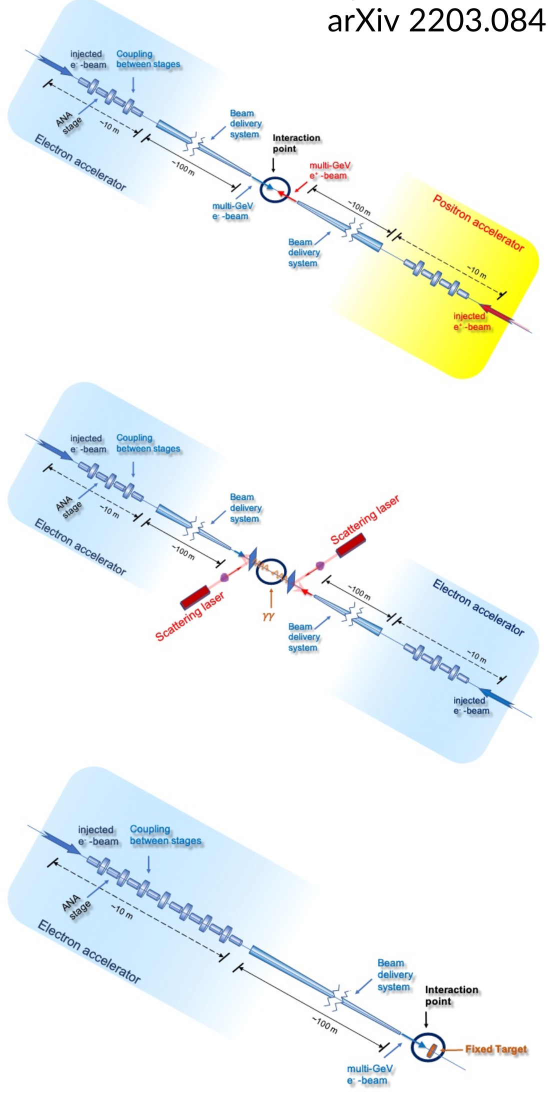
The Next Steps: Design Study and Demo Facility

In the near-term, the Wakefield Accelerator Community plans to contribute to self-consistent design studies of future colliders and near-term applications, alongside our European colleagues.

Ask to P5: The Wakefield Accelerator Community requests support for an Integrated Design Study from the newly-formed National Collider R&D initiative.

Before a Wakefield Collider at 15 TeV is built, an intermediate facility is needed.

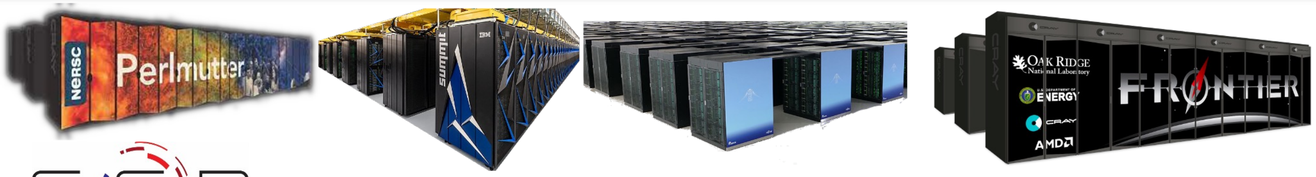
Future Request: An intermediate energy facility with multiple stages and novel BDS design will be used to demonstrate Wakefield Accelerator technology while pursuing near-term HEP applications.


Intermediate Energy Demonstrator
arXiv 2203.08425

Particle-in-Cell Simulations

WarpX 2022 Gordon Bell Prize winner

on the world's largest supercomputers



ECP
EXASCALE COMPUTING PROJECT

US-wide, Europe-wide & international collaborations

SciDAC Scientific Discovery through Advanced Computing

CAMPA

EuPRAXIA

ALEGRO 2023

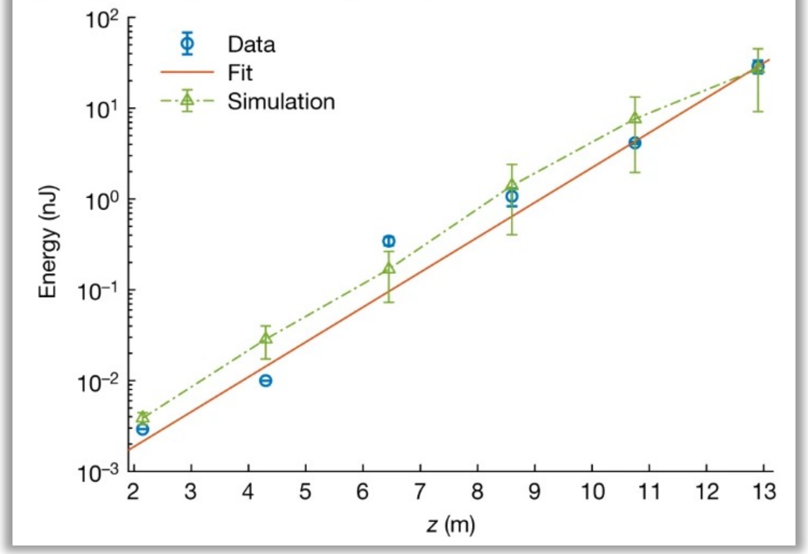
are developing the next generation of simulation tools.

- Novel community integrated ecosystem of codes is being assembled for design of conventional, AAC and hybrid colliders.
- From fast reduced/surrogate models for design to large scale first-principle for studies.

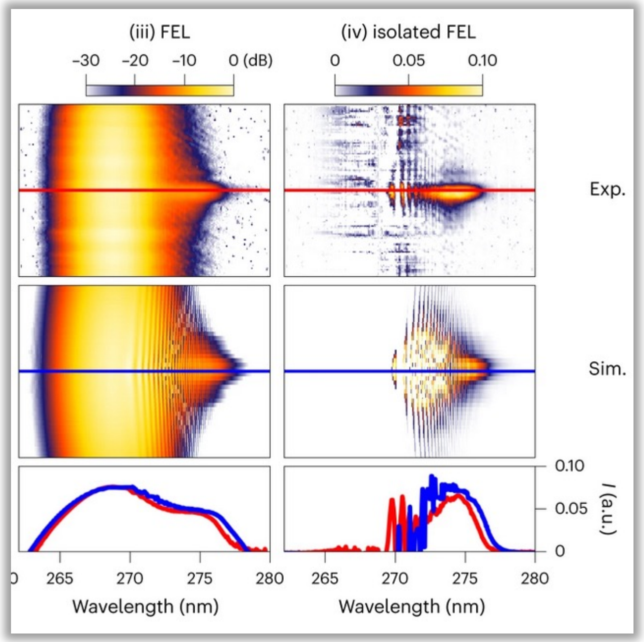
Near Term Applications

W. Wang et. al. Nature (2021)

Fig. 3: Exponential growth of the amplified light.



R. Pompili et. al. Nature (2022)



M. Labat et. al. Nat. Phot. (2022)

Three demonstrations of plasma-driven FEL within one year, all outside of U.S.

Near Term Applications

The international journal of science / 22 July 2021

nature

COMPACT SOURCE

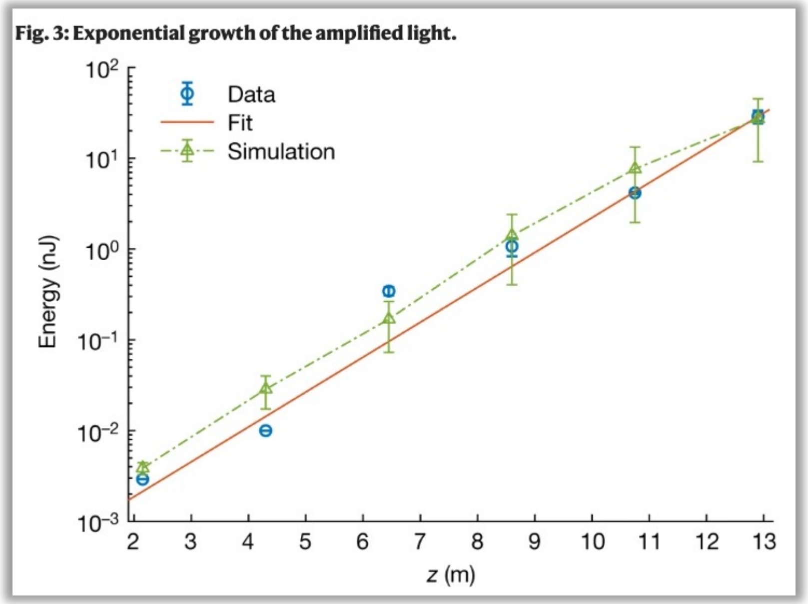
Plasma-based acceleration paves way to smaller free-electron lasers

Firearm focus Fresh funding boosts US studies on gun violence

Detecting emissions How to verify compliance with Paris and Montreal treaties

Flow charts How fluid dynamics help a deep-sea sponge feed and reproduce

W. Wang et. al. Nature (2021)



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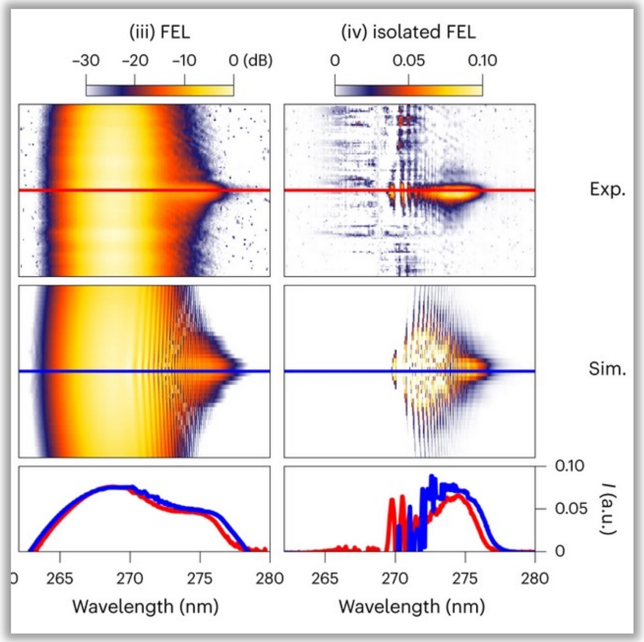

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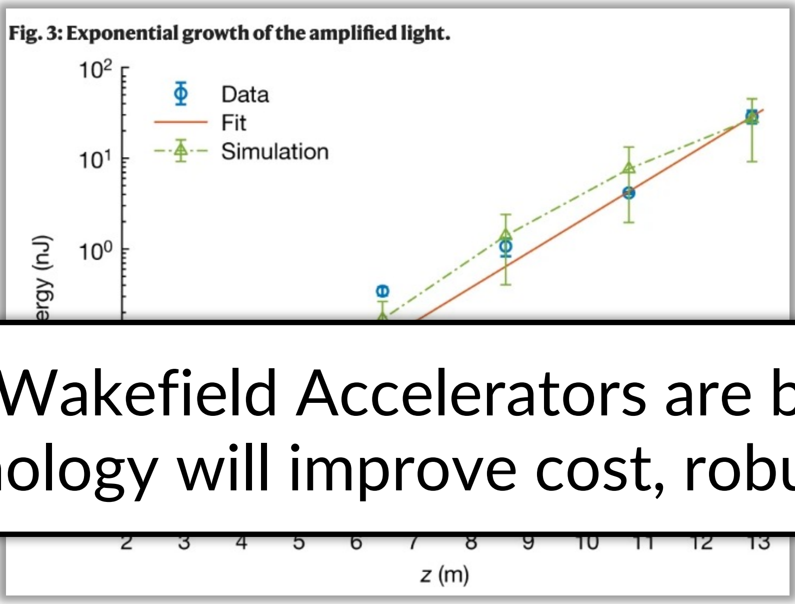
FEL gain observed at LBNL last month!

Near Term Applications

See Short Remark by Claudio Emma on Near-Term Applications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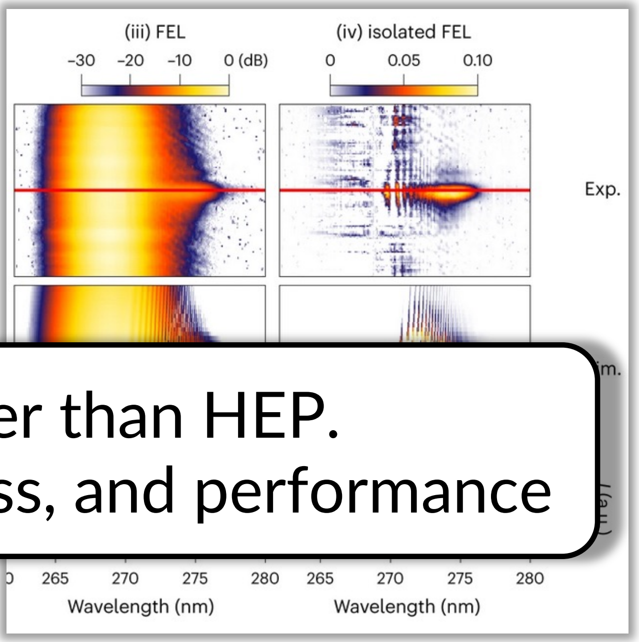

Applications of Wakefield Accelerators are broader than HEP.
More uses of this technology will improve cost, robustness, and performance

W. Wang et. al. Nature (2021)

R. Pompili et. al. Nature (2022)

M. Labat et. al. Nat. Phot. (2022)

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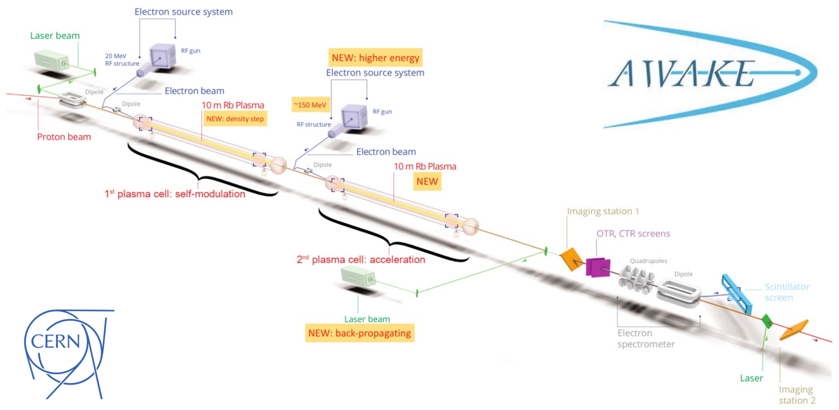
European Efforts

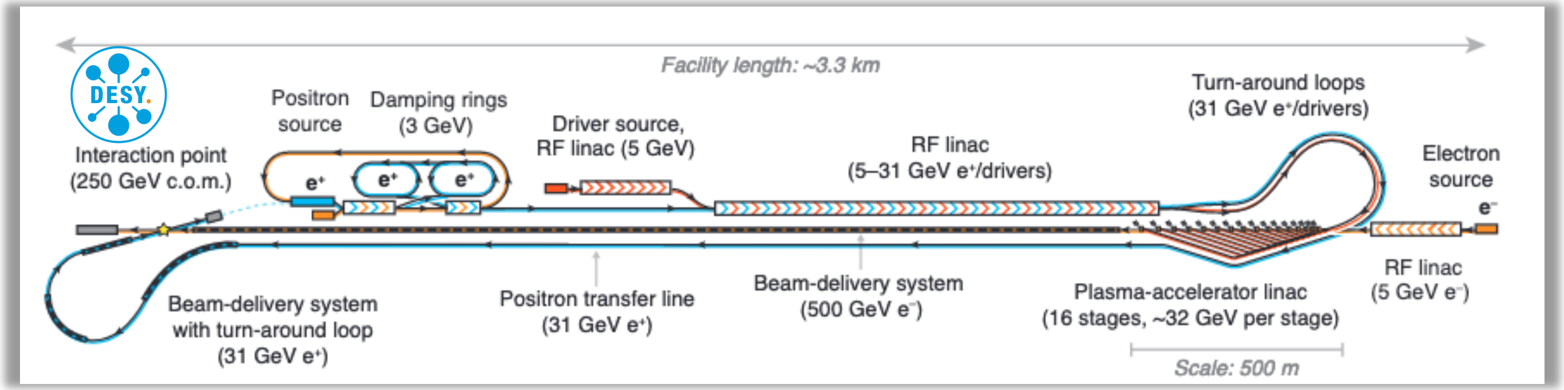
Europe is moving ahead with major Wakefield Accelerator projects, such as AWAKE at CERN, and EuPRAXIA User Facility at INFN, which is on ESFRI Roadmap.

New ideas like Hybrid PWFA Boosted Higgs Factory will be covered in an Integrated Design Study.

Support from P5 is critical for keeping pace with our European Partners!



AWAKE: Proton-driven PWFA for experiment at CERN aims to generate O(100) GeV electrons for Dark Sector searches.



Plasma Collider Boosted Higgs Factory, B. Foster et al. arXiv:2303.10150

EuPRAXIA Plasma Accelerator User Facility at INFN

European Efforts

ESPP High-priority future initiatives:

Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs.

The European particle physics community must intensify accelerator R&D and sustain it with adequate resources.

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User

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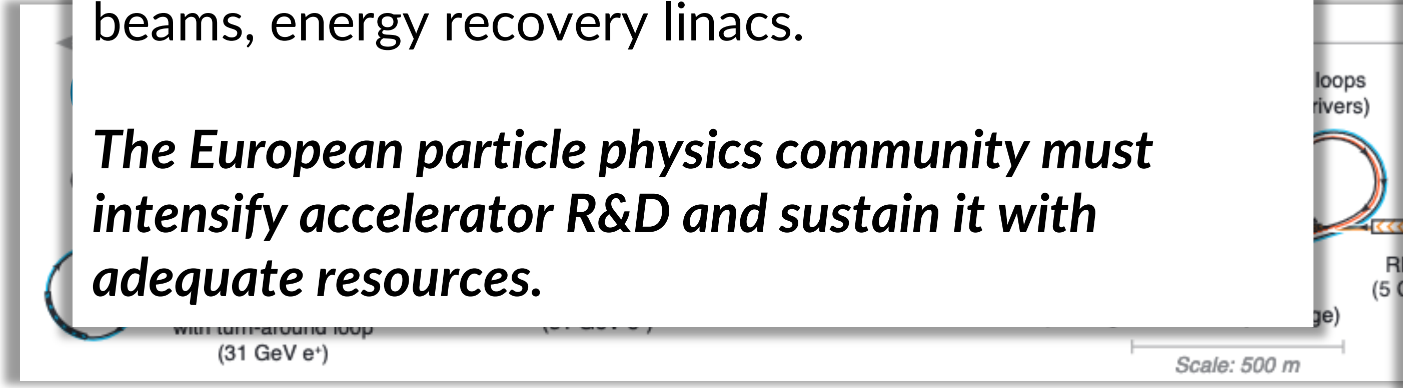

Plasma Collider Boosted Higgs Factory, B. Foster et al. arXiv:2303.10150


2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy
Update

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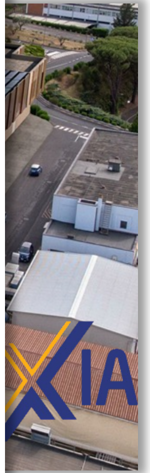
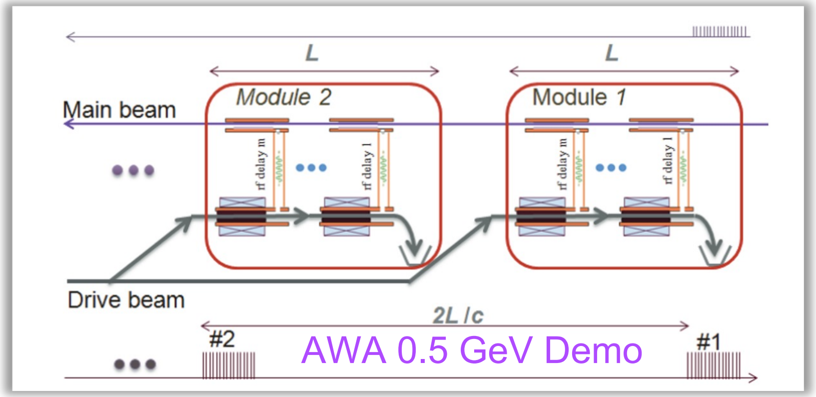


y at INFN

Facility Upgrade Summary

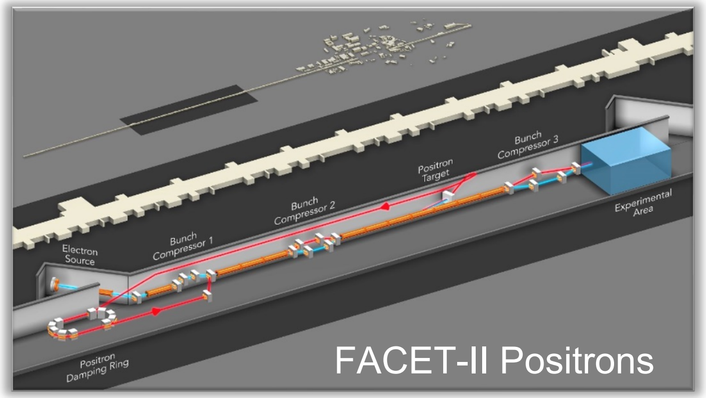
The **AWA Upgrade** will demonstrate a 0.5-GeV module as the basis for a future multi-TeV collider.

- Cost estimate is approx. $15M.
- Internally costed for ANLHEP strategic planning exercise.



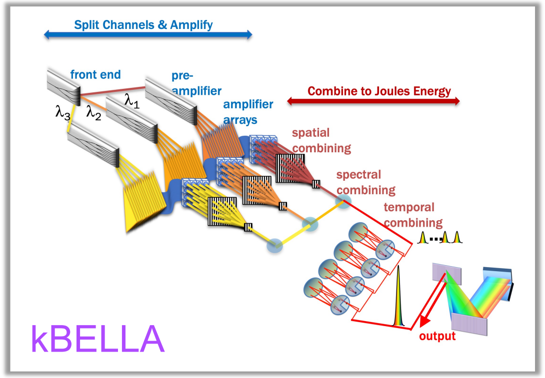
The **FACET-II Positron Upgrade** will enable electron beam-driven positron acceleration in plasma. FACET-II is the only facility in the world that can support this research.

- Received CD2 approval. Descoped in 2018.
- Listed in last P5 and ARDS reports.
- Cost estimate is approx. $50M + 5 years of operation.



kBELLA will enable kHz rep-rate precision LWFA. This addresses major risks for a multi-TeV collider and enables near term applications.

- Costed by FESAC and LBNL review.
- Listed in last P5 and ARDS reports.
- Cost estimate is approx. $100M



Risk-Retirement Table

- 🟢 R&D underway
- ○ R&D planned
- 🟠 Facility Upgrade Planned
- ◯ Possible at Future Facility

There are plans to address much of the risk to a 10 TeV-scale collider at existing Test Beam Facilities.

However, there are key R&D advances that require facility upgrades.

Facility upgrades are key to retiring risks for the 10 TeV-scale collider.

Upgrades will enable near-term HEP applications!

		Existing Facilities			Planned Facilities			Future Facilities		
		AWA	FACET-II	BELLA	AWA 0.5 GeV	FACET-II Posi.	kBELLA	PWFA Staging	AWA 3 GeV	BDS Demo
SWFA	High-Power R&D	🟢			🟠				◯	
	High-Efficiency	🟢			🟠				◯	
	Drive beam generation								◯	
	High-Quality multistage	○			🟠				◯	
	Novel BDS									◯
PWFA	High-Quality single-stage		🟢			🟠		◯		
	In-out coupling		🟢			🟠		◯		
	Controlled injection		🟢							
	High Repetition Rate		FLASHForward					◯		
	Positron PWFA					🟠				
	Staging							◯		
	Energy Recovery		○			🟠				
	Novel BDS		○							◯
LWFA	High-Quality single-stage			🟢			🟠			
	Staging			🟢			🟠			
	Controlled injection			🟢			🟠			
	High Repetition Rate						🟠			
	Positron LWFA			○						
	Energy Recovery			○			🟠			
	Novel BDS									
$\gamma\gamma$	NLQED		🟢	○						◯
	FEL R&D		○	○						
	IP Design									◯

Risk-Retirement Table

● R&D underway
○ R&D planned
🟠 Facility Upgrade Planned
◯ Possible at Future Facility

There are plans to address much of the risk to a 10-TeV scale collider at existing Test Beam Facilities.

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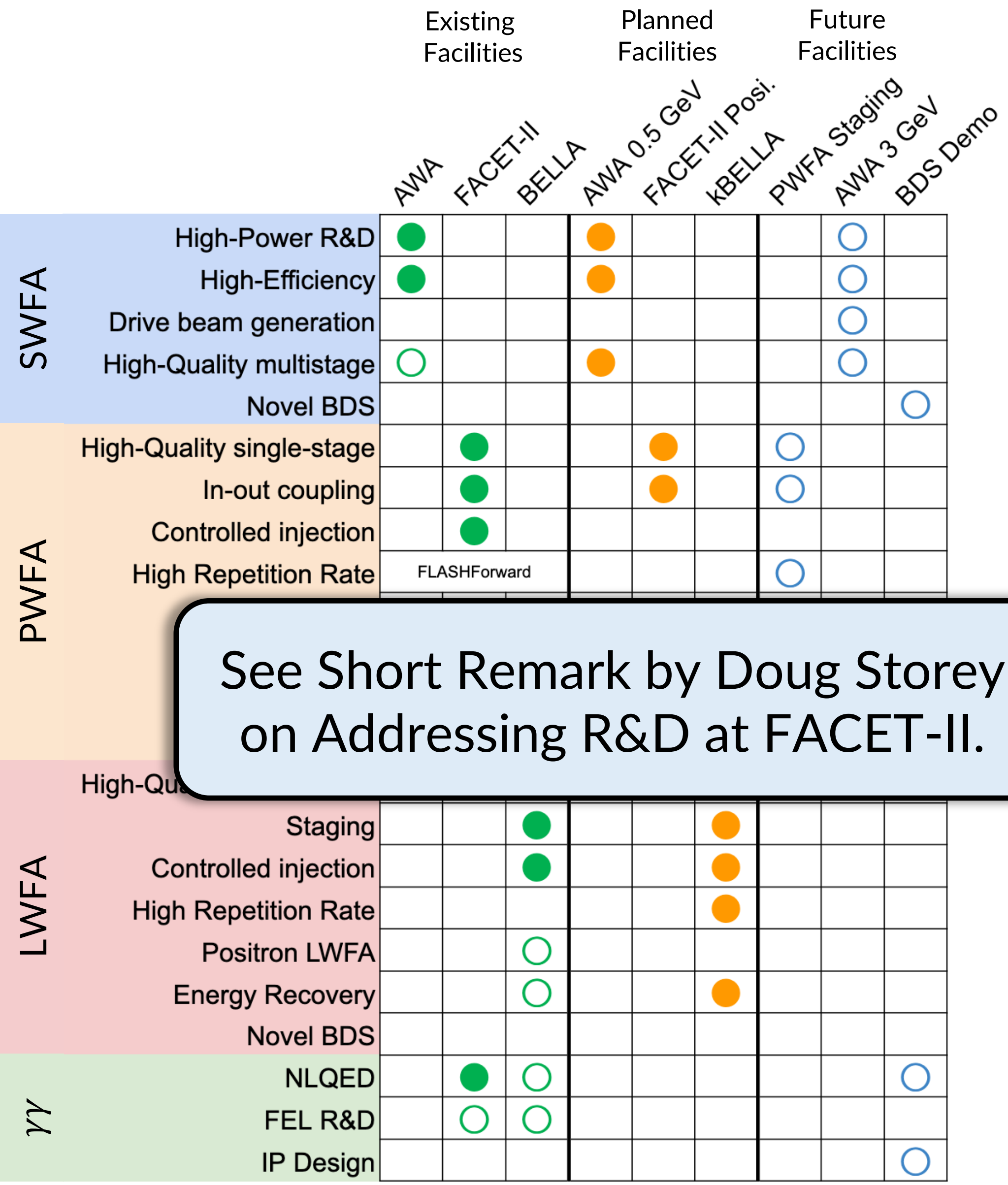


		Existing Facilities			Planned Facilities			Future Facilities		
		AWA	FACET-II	BELLA	AWA 0.5 GeV	FACET-II Posi.	kBELLA	PWFA Staging	AWA 3 GeV	BDS Demo
SWFA	High-Power R&D	●			🟠				◯	
	High-Efficiency	●			🟠				◯	
	Drive beam generation								◯	
	High-Quality multistage	○			🟠				◯	
	Novel BDS									◯
PWFA	High-Quality single-stage		●			🟠		◯		
	In-out coupling		●			🟠		◯		
	Controlled injection		●							
	High Repetition Rate		FLASHForward					◯		
LWFA	High-Qu									
	Staging			●			🟠			
	Controlled injection			●			🟠			
	High Repetition Rate						🟠			
	Positron LWFA			○						
	Energy Recovery			○			🟠			
	Novel BDS									
$\gamma\gamma$	NLQED		●	○						◯
	FEL R&D		○	○						
	IP Design									◯

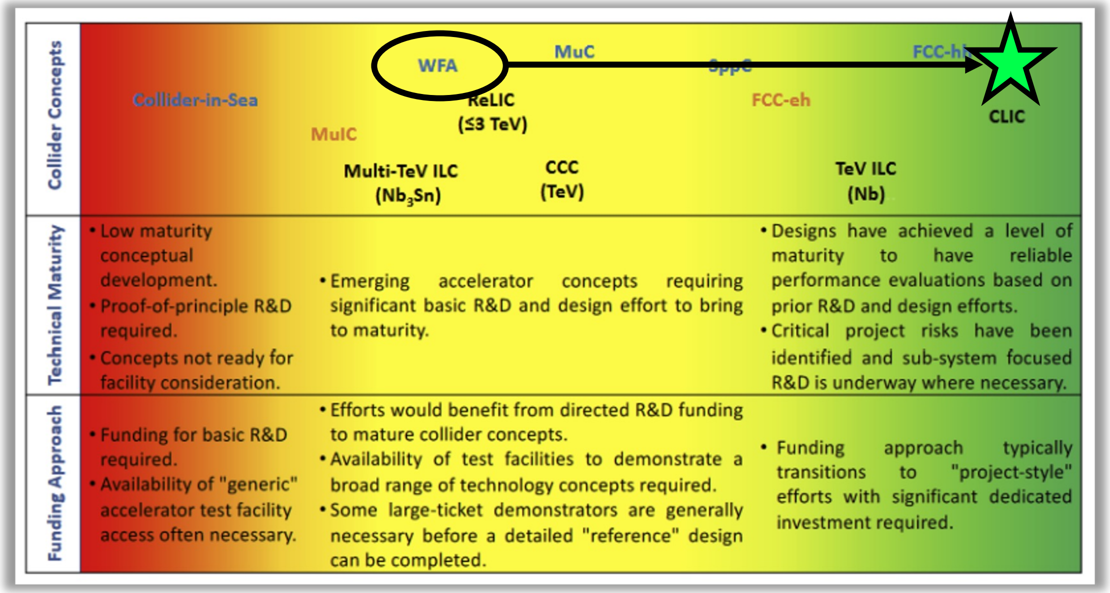
See Short Remark by Doug Storey on Addressing R&D at FACET-II.

Requests to P5 in Support of 10+ TeV Collider

1. Strengthen support for Wakefield Accelerator R&D through the HEP GARD program.
    - Critical for Workforce Development.
    - Continue to retire R&D risks.
2. Support for upgrades to Beam Test Facilities. Retire the next generation of risks.
    - AWA 0.5-GeV Demonstrator Upgrade.
    - FACET-II Positron Upgrade.
    - kBELLA kHz LWFA Upgrade.
3. Support for an Integrated Design Study on future Wakefield Colliders, in collaboration with our European Partners, with funding through the new National Collider R&D initiative.

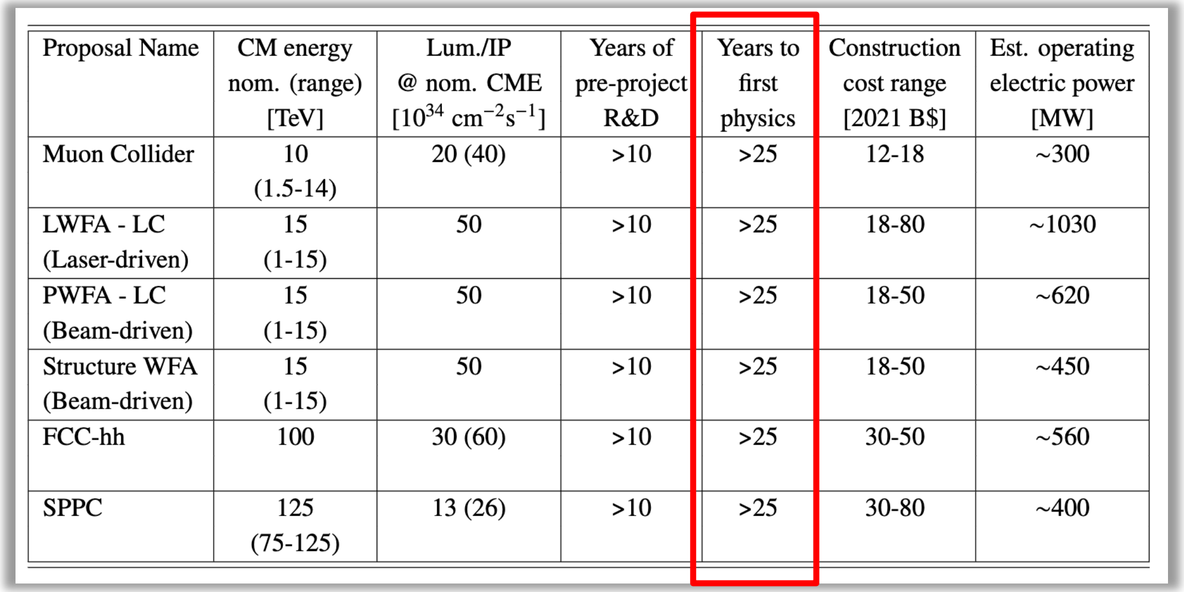
Conclusion:

Snowmass AF4 Energy Frontier Colliders



Technical Maturity	• Low maturity conceptual development. • Proof-of-principle R&D required. • Concepts not ready for facility consideration.	• Emerging accelerator concepts requiring significant basic R&D and design effort to bring to maturity.	• Designs have achieved a level of maturity to have reliable performance evaluations based on prior R&D and design efforts. • Critical project risks have been identified and sub-system focused R&D is underway where necessary.
Funding Approach	• Funding for basic R&D required. • Availability of "generic" accelerator test facility access often necessary.	• Efforts would benefit from directed R&D funding to mature collider concepts. • Availability of test facilities to demonstrate a broad range of technology concepts required. • Some large-ticket demonstrators are generally necessary before a detailed "reference" design can be completed.	• Funding approach typically transitions to "project-style" efforts with significant dedicated investment required.

Snowmass Implementation Task Force



Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

The only way to make our 10+ TeV dreams a reality is by committing to Accelerator R&D today.

Acknowledgements

Eric Esarey, Carl Schroeder, Jeroen van Tilborg, Tony Gonsalves, Jean-Luc Vay

Chunguang Jing, Philippe Piot, Xueying Lu, John Power

Mark Hogan

The Snowmass AF6 Conveners:
Cameron Geddes, Ralph Assmann, Pietro Musemecci, Mark Hogan

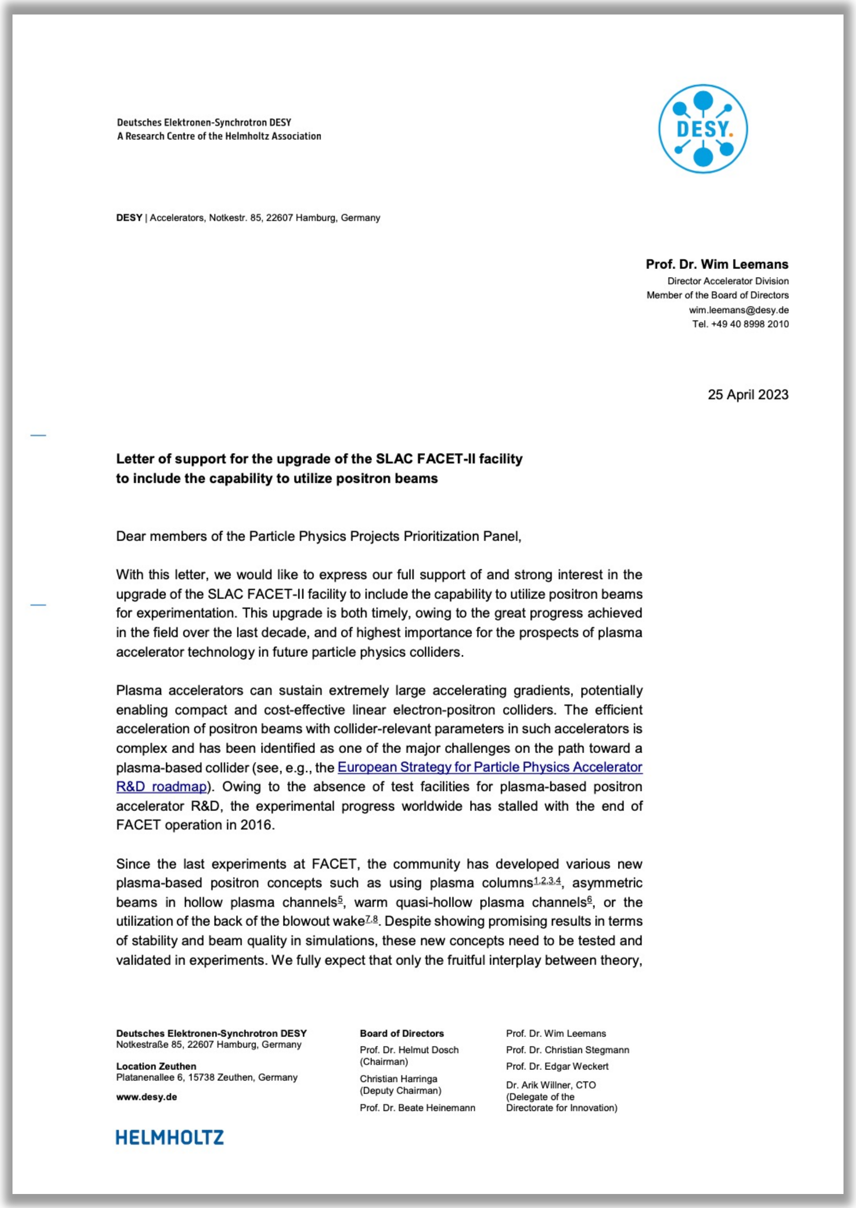
Snowmass AF6 Report: https://arxiv.org/abs/2208.13279

Synergies

There are many synergies between Wakefield Accelerator Research and other Collider Concepts being discussed today:

- The C^3 Demo Facility can host the first beam-driven plasma staging experiment.
- Generic Particle-in-Cell (PIC) codes are being adapted to address beamstrahlung physics at very high energies. These codes will be capable of simulating ILC, CLIC, and C^3 collisions with much greater detail.
- PIC codes may also be needed for modeling muon beam-plasma interaction in ionization cooling channels.
- Wakefield Accelerators can provide low-emittance electron beams for collisions or positron beam sources.

Letter from DESY in support of Positrons at FACET-II



Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

DESY | Accelerators, Notkestr. 85, 22607 Hamburg, Germany

Prof. Dr. Wim Leemans
Director Accelerator Division
Member of the Board of Directors
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Tel. +49 40 8998 2010

25 April 2023

Letter of support for the upgrade of the SLAC FACET-II facility to include the capability to utilize positron beams

Dear members of the Particle Physics Projects Prioritization Panel,

With this letter, we would like to express our full support of and strong interest in the upgrade of the SLAC FACET-II facility to include the capability to utilize positron beams for experimentation. This upgrade is both timely, owing to the great progress achieved in the field over the last decade, and of highest importance for the prospects of plasma accelerator technology in future particle physics colliders.

Plasma accelerators can sustain extremely large accelerating gradients, potentially enabling compact and cost-effective linear electron-positron colliders. The efficient acceleration of positron beams with collider-relevant parameters in such accelerators is complex and has been identified as one of the major challenges on the path toward a plasma-based collider (see, e.g., the European Strategy for Particle Physics Accelerator R&D roadmap). Owing to the absence of test facilities for plasma-based positron accelerator R&D, the experimental progress worldwide has stalled with the end of FACET operation in 2016.

Since the last experiments at FACET, the community has developed various new plasma-based positron concepts such as using plasma columns[1,2,3,4], asymmetric beams in hollow plasma channels[5], warm quasi-hollow plasma channels[6], or the utilization of the back of the blowout wake[7,8]. Despite showing promising results in terms of stability and beam quality in simulations, these new concepts need to be tested and validated in experiments. We fully expect that only the fruitful interplay between theory,

simulations, and experiments can yield the progress required for a plasma-based collider. While we are willing to contribute to both theory and simulations, the positron upgrade at FACET-II is currently the only viable experimental option to enable plasma-based positron accelerator research worldwide.

We consider the positron upgrade at FACET-II to be important and timely to maintain the high momentum in the plasma-based community. An experimental facility is a significant and necessary step toward a plasma-based collider, and we fully support extending the experimental capabilities of FACET-II in this direction. Furthermore, the proposed upgrade enables relevant advanced accelerator research in other fields such as in structure-based wakefield positron acceleration.

With this letter we want to express our strongest support for the planned positron upgrade at FACET-II.

Thank you for your consideration.

Sincerely,

Prof. Dr. Wim Leemans

Dr. Jens Osterhoff

THÉVENET
Dr. Maxence Thévenet

Dr. Severin Diederichs