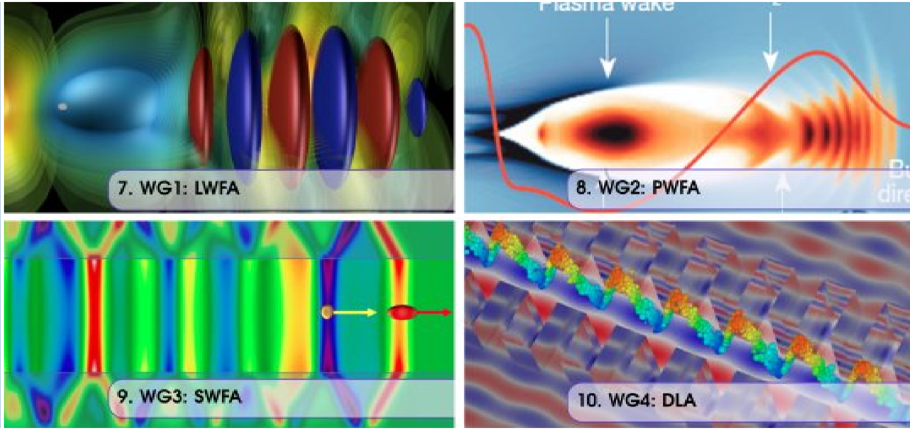
ICFA Seminar DESY, November, 30th 2023

International Committee for Future Accelerators

Panel on Advanced and Novel Accelerators

Wakefield Accelerators (WFAs)



Presented by Philippe Piot
(member of ICFA/ANA panel)

Argonne National Laboratory

& Northern Illinois University

w/ input from ICFA/ANA panel members and materials from S. Gessner (SLAC)

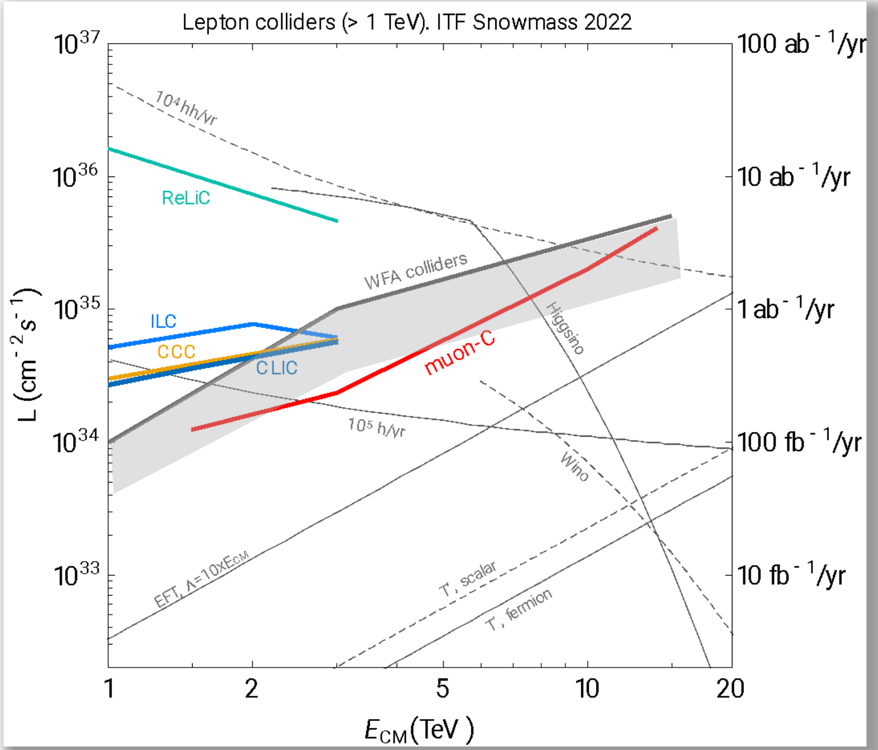
Northern Illinois University Argonne NATIONAL LABORATORY

MOTIVATIONS FOR A WFA-BASED COLLIDER

Attaining the 10-TeV energy frontier

(adapted from Snowmass report)

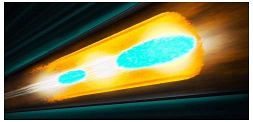
- **Physics motivation (you know better!)**
  - From the executive summary of the 2022 Snowmass Energy Frontier report *"While the naturalness principle suggests new physics to lie at mass scales close to the electroweak scale, in many cases direct searches for specific models have placed strong bounds 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)."*

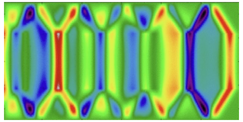


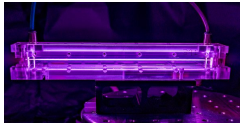
- **Opportunities**
  - Decrease linear-collider size
  - Lower capital and operating costs
  - Reduce environmental impact

WAKEFIELD ACCELERATORS

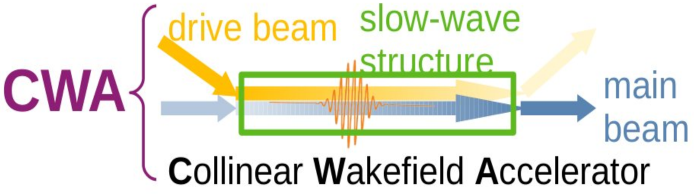
Overview



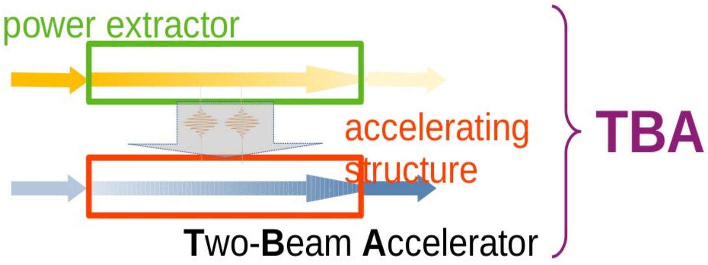




- **Advantages:**
  - Support high accelerating gradients ~O(1-10 GeV/m)
  - Well-suited for short-bunch acceleration (e.g. for beamstrahlung suppression)

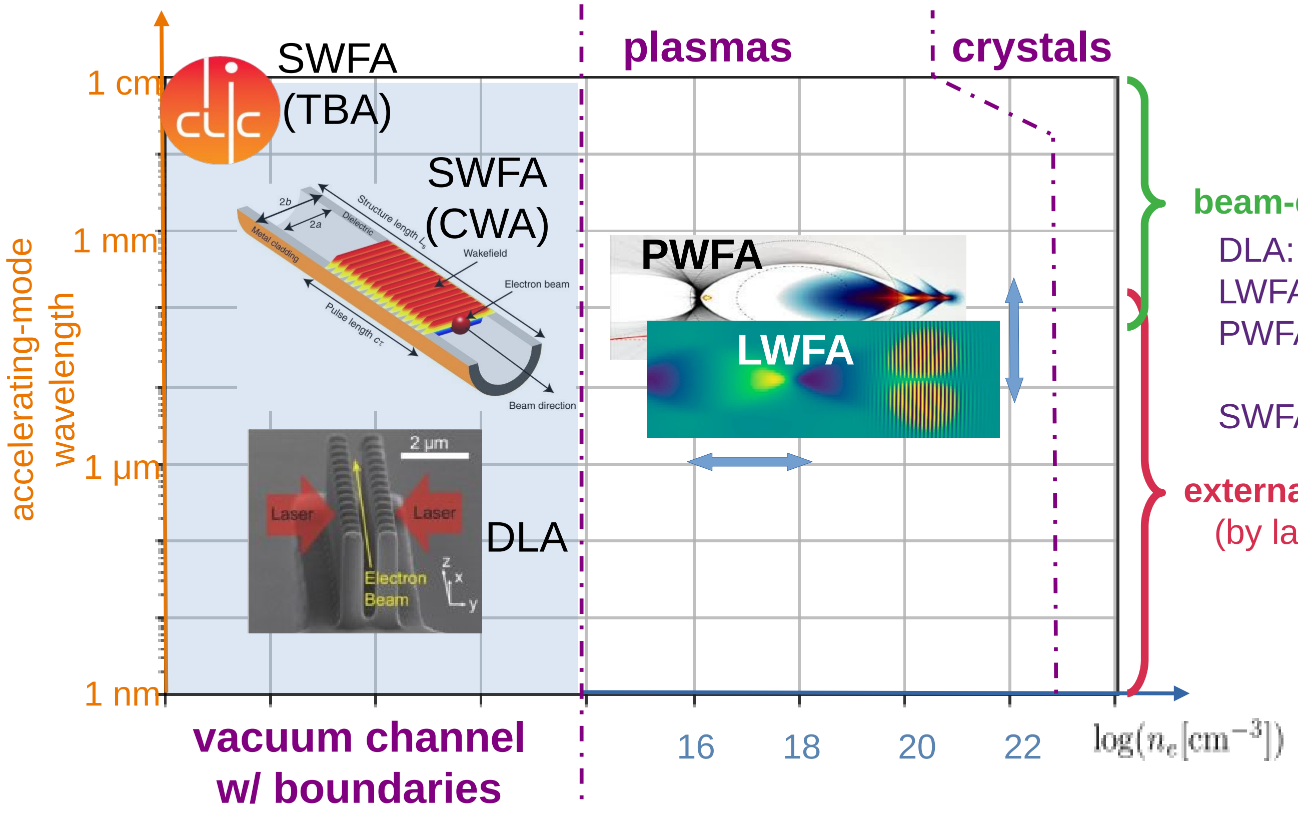


- **Current research focus:**
  - **High accelerating gradients:** in single and ultimately cascaded configurations (staging)
  - **High efficiency:** plasma/structure and drive-beam (laser/particle) optimization
  - **High-quality beams:** preservation of emittance, control of energy spread, mitigation of instabilities



WAKEFIELD ACCELERATOR TECHNOLOGIES

Overview



beam-driven

DLA: **D**ielectric **l**aser **a**ccelerator
LWFA: **L**aser **WFA**
PWFA: **P**lasma **WFA**
drive: e- and p (AWAKE)
SWFA: **S**tructure **WFA**

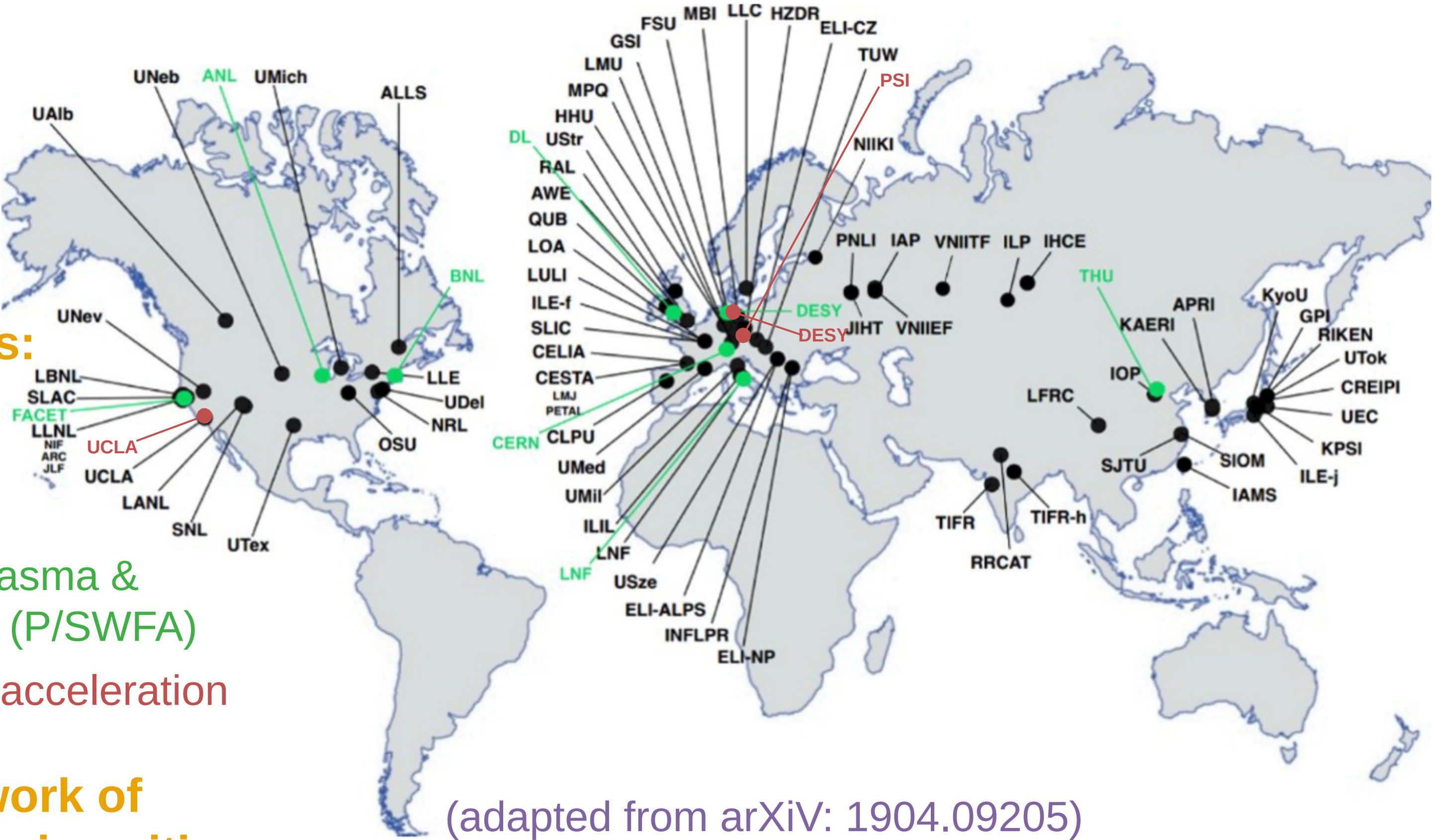
externally powered
(by lasers, FELs)

http://cds.cern.ch/record/2298632

WFA RESEARCH EFFORT

A global enterprise

- **>80 groups:**
  - Asia:~20
  - Europe: ~40
  - America: ~20
- **Research focus:**
  - Laser-driven plasma accel. (LWFA)
  - Beam-driven plasma & structure accel. (P/SWFA)
  - Dielectric laser acceleration (DLA)
- **Extensive network of collaborating universities**



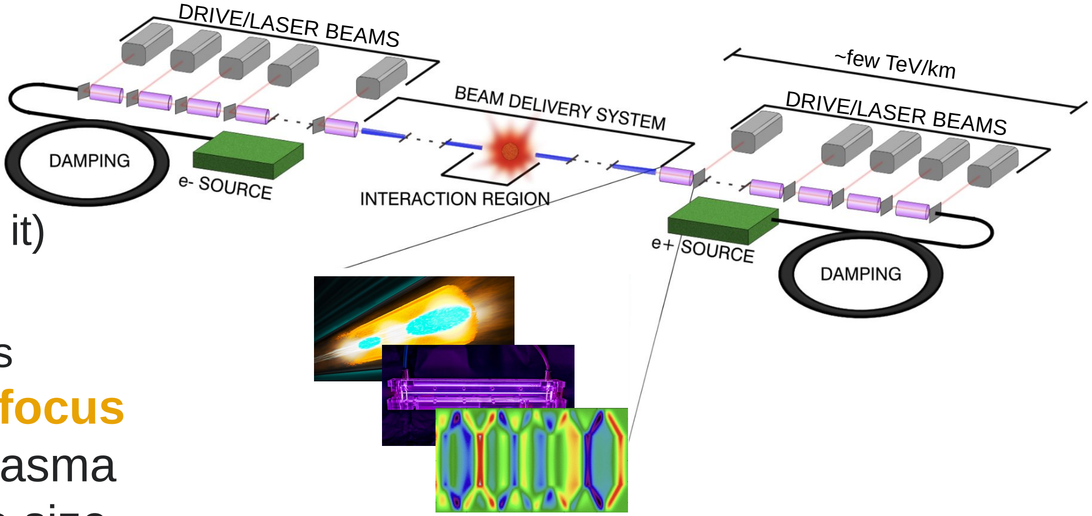
(adapted from arXiV: 1904.09205)

WFA-BASED LINEAR COLLIDER ARCHITECTURE

Similar to conventional linear colliders

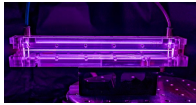
- **Sources/injector**
  - e+/e- conventional or advanced (plasma-based) sources
- **Phase-Space cooling**
  - Conventional (damping rings)
  - Phase-space repartitioning (if initial source quality allows for it)
- **Main linac**
  - Uses one of the WA technologies
- **Beam-Delivery System/Final focus**
  - plasma-based techniques (plasma lenses) offer a path to reduce size.

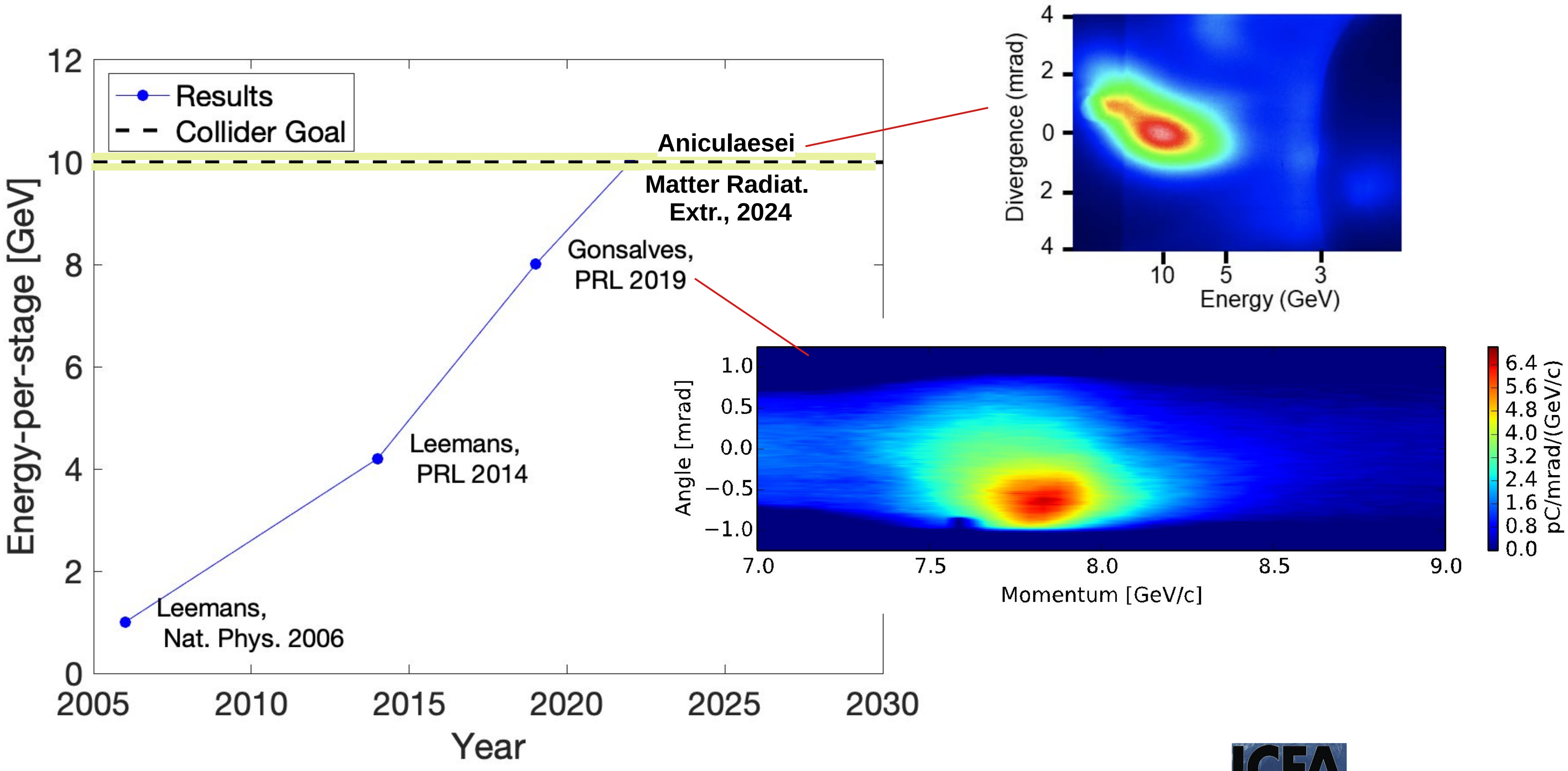
adapted from arXiv 2203.08366



ILLUSTRATIVE RECENT RESULTS

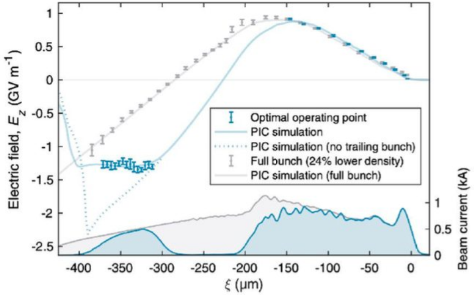
Performances of Laser-Wakefield Accelerators (LWFA)

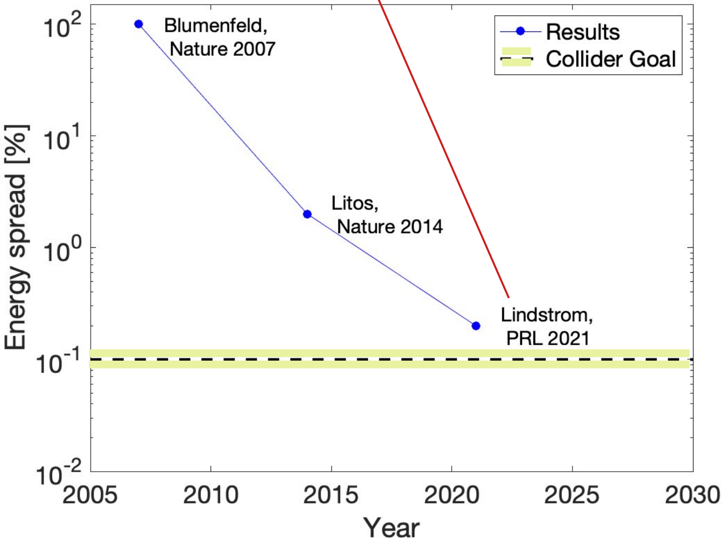


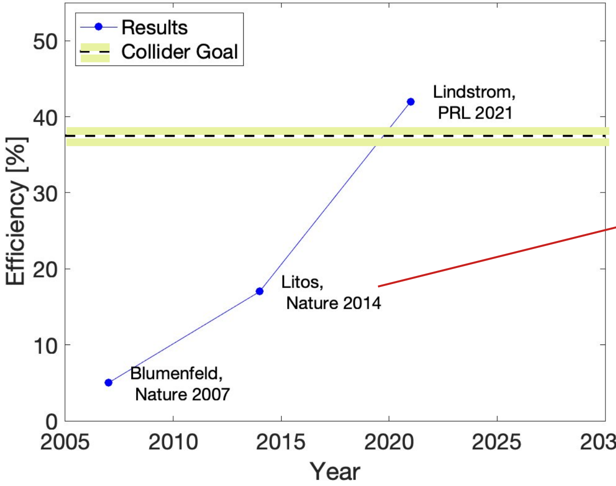


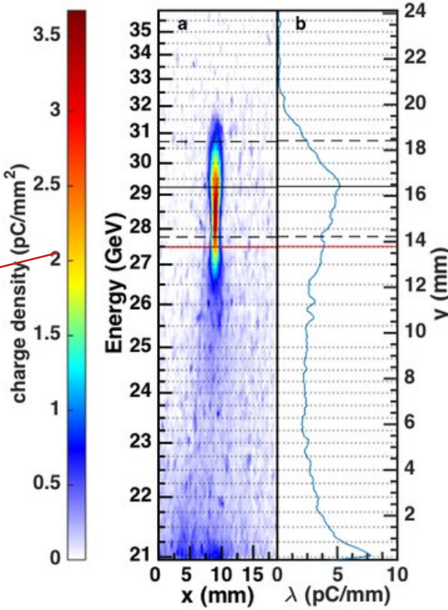
ILLUSTRATIVE RECENT RESULTS

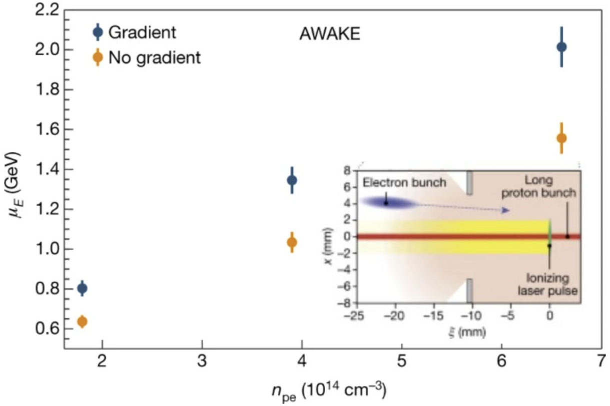
Performances of Plasma-Wakefield Accelerators (PWFA)











Using proton as drive beam (AWAKE@CERN); AWAKE coll., Nature, 2018

ICFA ANA

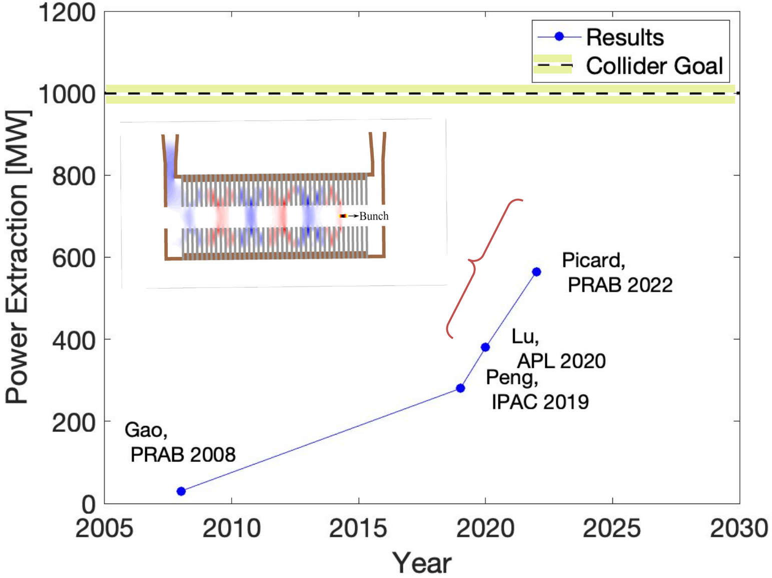
International Committee for Future Accelerators

Panel on Advanced and Novel Accelerators

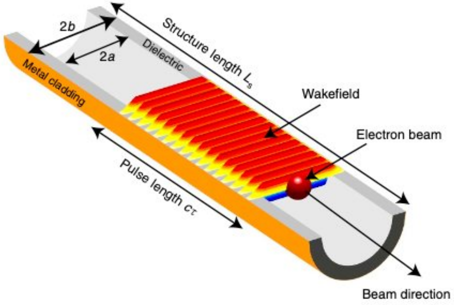
ILLUSTRATIVE RECENT RESULTS

Performances of Structure-Wakefield Accelerators (SWFA)

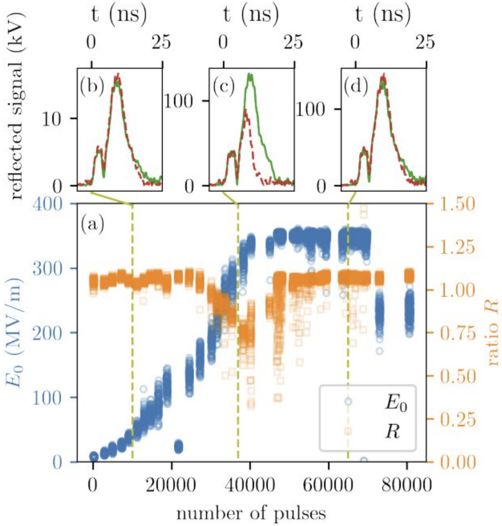
TBA



CWA



B. O'Shea Nat. Comm 2006: SWFA (dielectric) ~GV/m



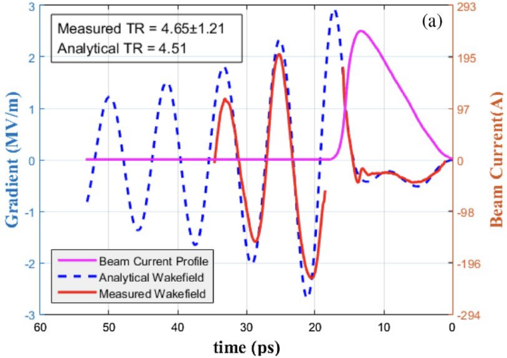
W.H. Tan, et al. PRAB 2022: SWFA (metal) ~0.4 GV/m

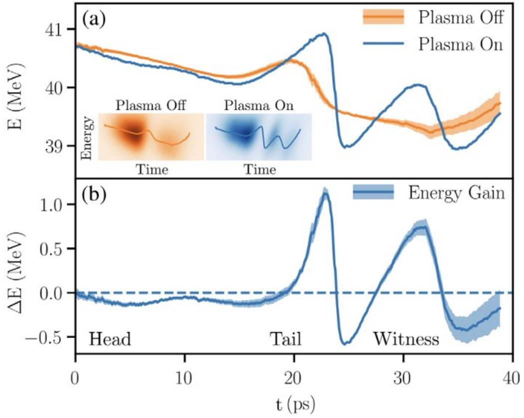
ONGOING R&D: IMPROVING EFFICIENCY

Transformer ratio and energy recovery

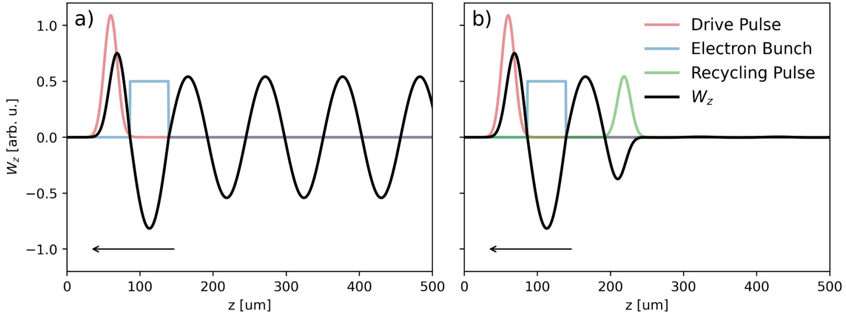
- **Maximize energy transfer from drive to main beam**
  - Beam shaping method
  - High transformer ratios attained in PWFA & SWFA
  - Ongoing R&D to combine high-efficiency with high-gradient (HEHG)
- **Energy recovery/recycling**
  - Use a pulse/beam downstream of the main bunch to recover the remaining energy in the wake.

Q. Gao, PRL 2018
Transformer ratio ~5





R. Roussel, PRL 2019
Transformer ratio ~7



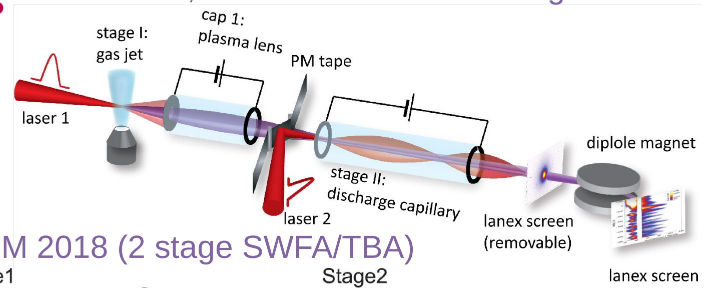
Proposed by M. Turner (CERN)

ONGOING R&D: STAGING & POSITRON ACCELERATION

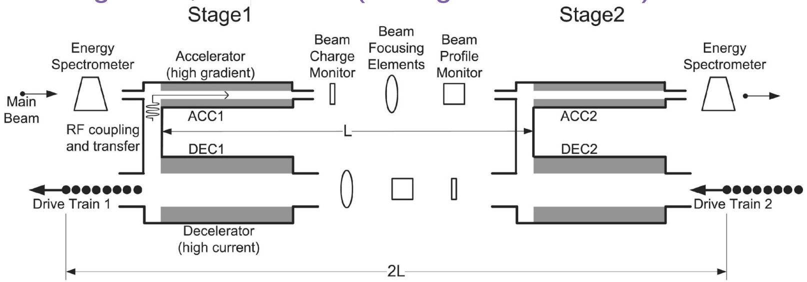
Demonstrating acceleration over long effective lengths
Producing Accelerating high-quality positron beams

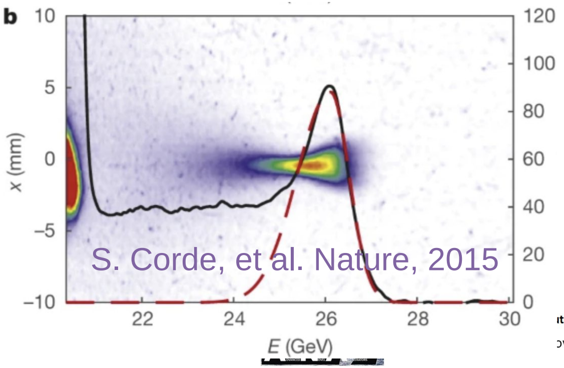
- **LWFA and SWFA staging demonstrations:**
  - Staging in LWFA (Bella) and SWFA (AWA) demonstrated
  - Further work on LWFA planned at Bella
- **PWFA staging in preparation**
  - Controlled in/out coupling at FACET2 and FlashForward
- **PWFA w/ proton driver (AWAKE)**
  - AWAKE run 2 will include two plasma cell to reach higher fields and control the beam quality.
- **PWFA for positrons (FACET/FACET2?)**
  - FACET inspired novel ideas for high-quality, stable acceleration of positrons in plasma.
  - Further work (staging) with e+ (FACET2)

S. Stenke, et al. Nature 2016: 2 stages LWFA.



C. Jing et al., NIM 2018 (2 stage SWFA/TBA)



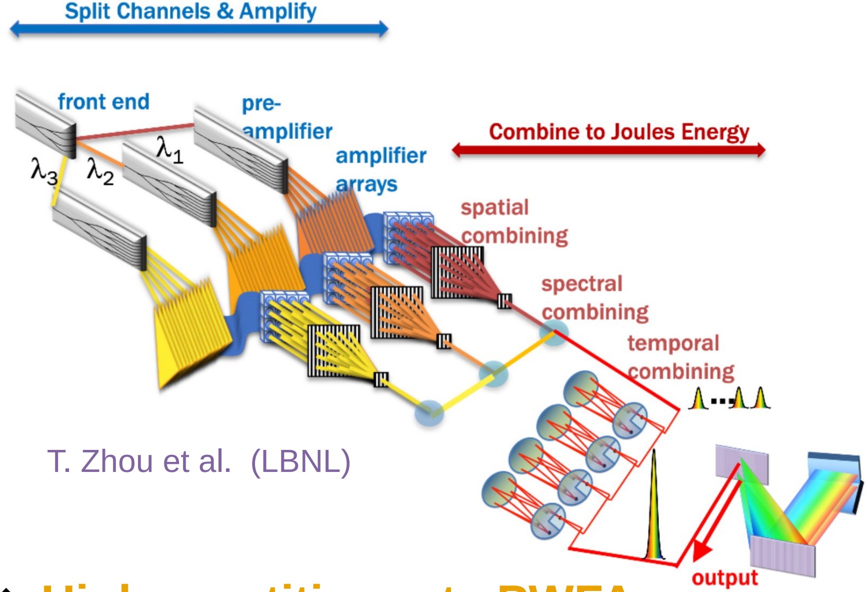


S. Corde, et al. Nature, 2015

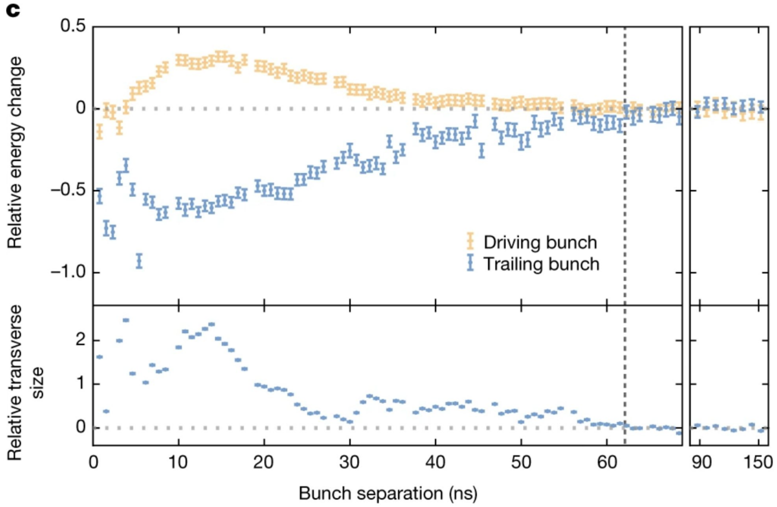
NEXT STEP: INCREASING REPETITION RATE

Enable by high-rep-rate lasers and drive beams

- **~kHz-class lasers required**
  - R&D at LBNL (kBella): coherent combining and efficiency improvement (fiber lasers)
  - R&D at DESY (Kaldera): Joule-class 1-kHz Titanium:Sapphire laser under development



T. Zhou et al. (LBNL)



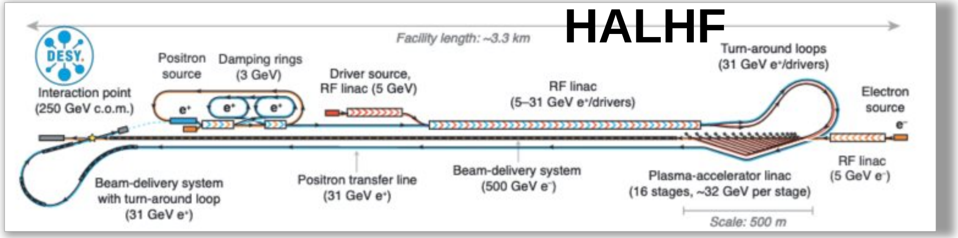
R. D'Arcy et al., Nature 2022

- **High-repetition rate PWFA explored @DESY (SRF linac)**
  - Recombination time ~60 ns
  - Plasma should support MHz repetition rate in PWFA or LWFA

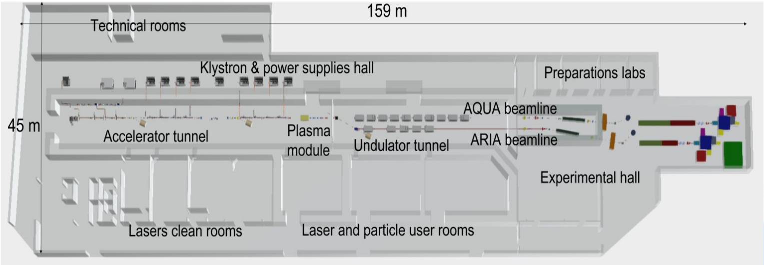
PATH TO A PHYSICS-ENABLING DEMO MACHINE

Several paradigms and facilities

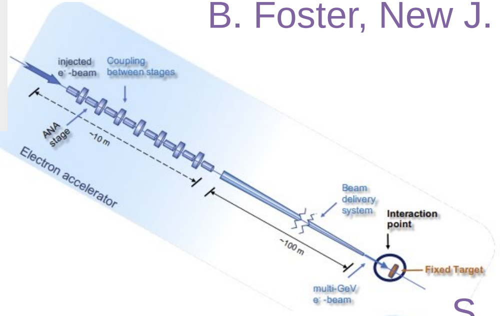
HALHF

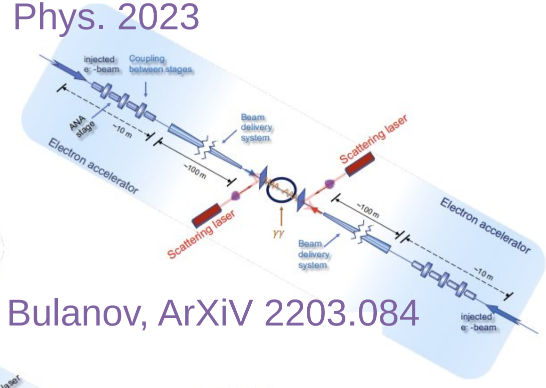


B. Foster, New J. Phys. 2023

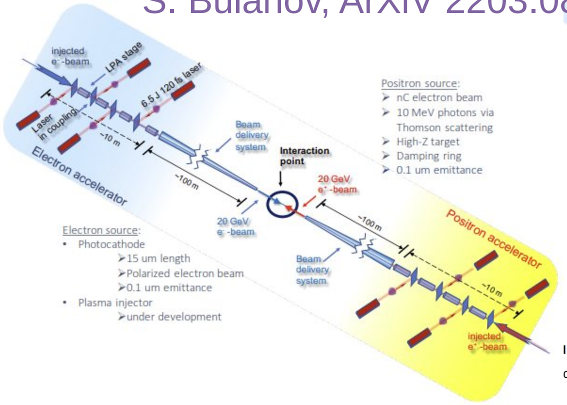


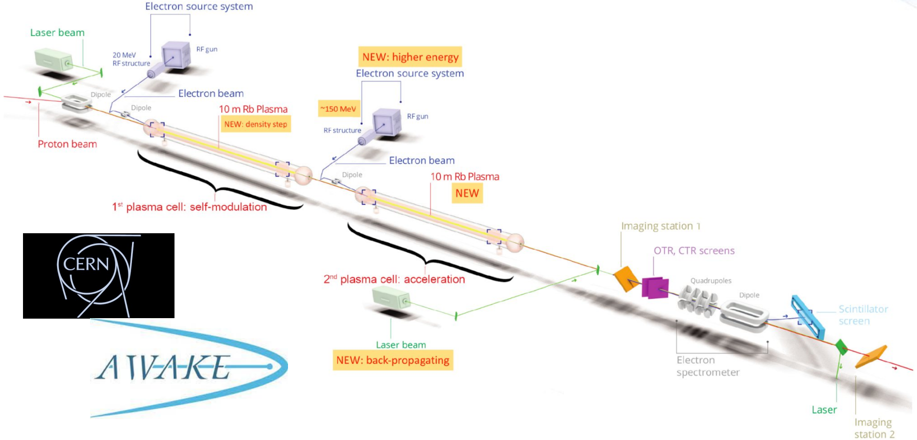
EuPRAXIA@SPARC_LAB





S. Bulanov, ArXiV 2203.084



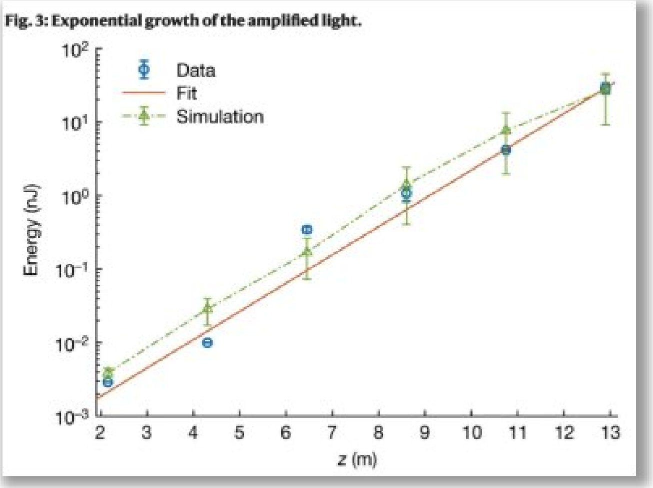


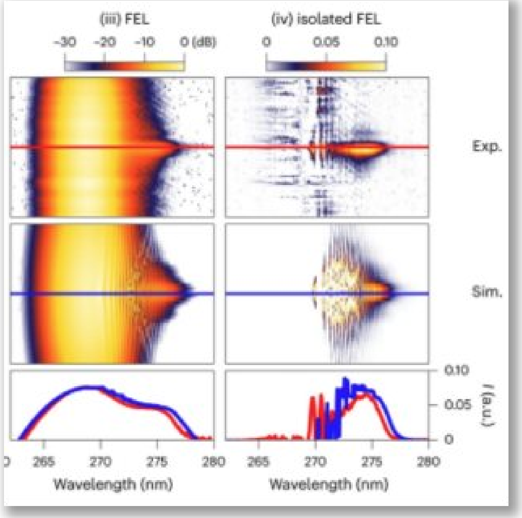
l Committee for Future Accelerators

dvanced and Novel Accelerators

POTENTIAL FOR BROADER IMPACTS

PWFA and LWFA have supported free-electron laser (FEL) lasing





W. Wang, et al. Nature, 2021:
27 nm SASE FEL driven by a LWFA

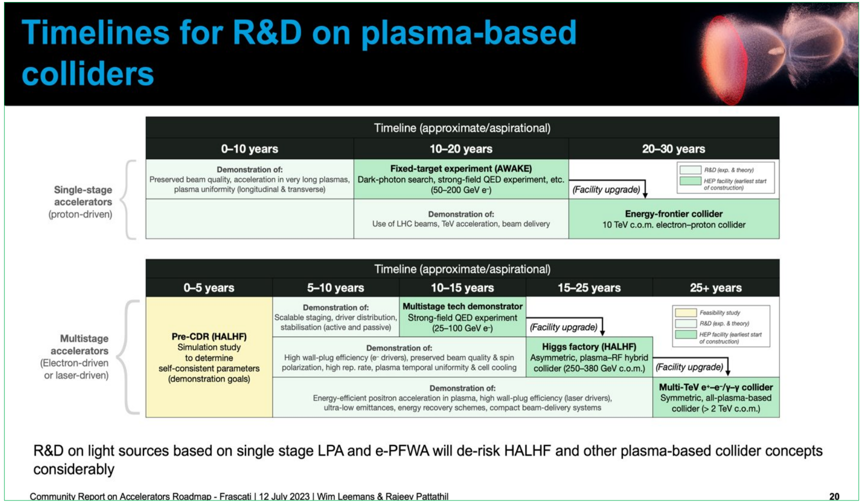
R. Pompili, et al. Nature, 2022:
820 nm SASE FEL w/ PWFA booster

M. Labat, et al. Nat. Phot., 2022:
270 nm seeded SASE FEL driven by a LWFA

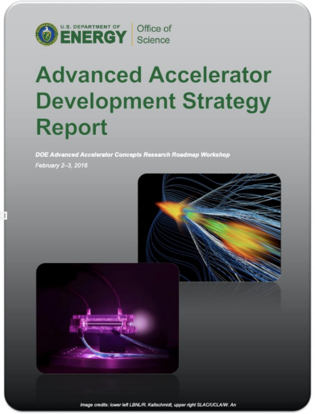
- The demonstrations of FEL lasing confirms the quality of the beams from WFAs.
- Broader applications of WFAs will help support development towards particle physics goals and may help reduce overall R&D cost.

ROADMAP TOWARD A COLLIDER

Roadmaps have been developed in Europe and the US



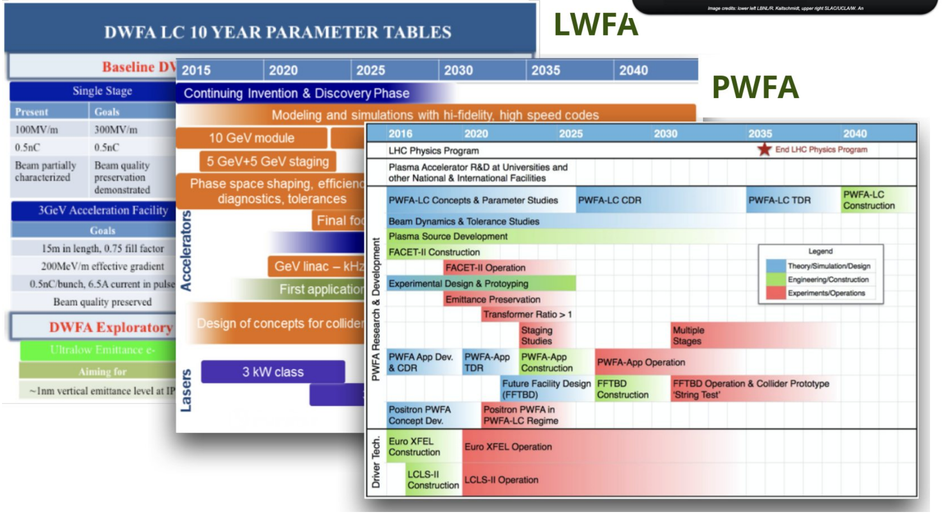
2016 US roadmap for Advanced Accelerator R&D



SWFA

LWFA

PWFA



European Strategy for Particle Physics

Accelerator R&D Roadmap

Editor: N. Mounet (CERN, Geneva, Switzerland)

2021 ESPP Accelerator R&D roadmap

High-gradient plasma and laser accelerators

Panel members: R. Assmann[e,f,+] (Chair), E. Gschwendtner[a] (Co-Chair), K. Cassou[c], S. Corde[z], L. Corner[i], B. Cros[aa], M. Ferrario[f], S. Hooker[bb], R. Ischebeck[g], A. Latina[a], O. Lundh[cc], P. Muggli[dd], P. Nghiem[b], J. Osterhoff[e], T. Raubenheimer[w,ee], A. Specka[ff], J. Vieira[gg], M. Wing[hh]

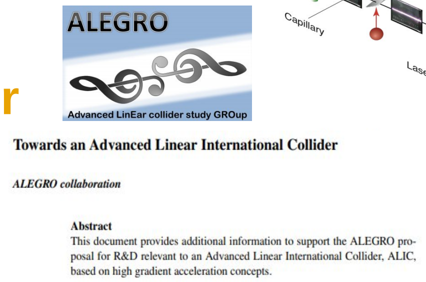
Associated members: C. Geddes[p], M. Hogan[w], W. Lu[v], P. Musumeci[ii]

ICFA/ANA-DRIVEN INITIATIVE

Advanced Linear Collider (ALIC)

- **Study group toward an WA-based collider**
  - Joint force/share resources: WA technologies have similarities (drive bunch, final focus,...)
  - Devise a global strategy
  - Organize the ALEGRO workshop series

    (ALEGRO24 in Lisbon 19-22 March 2024)


ALEGRO

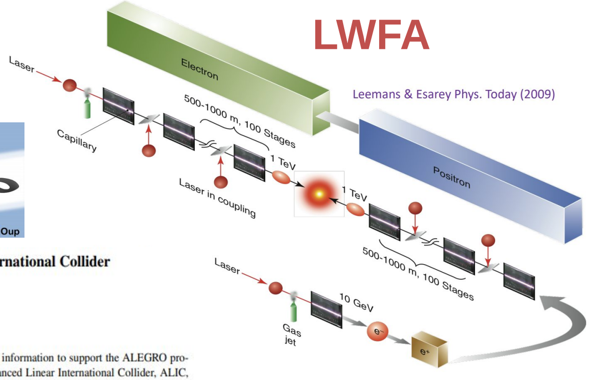
Advanced LinEar collider study GROup

Towards an Advanced Linear International Collider

ALEGRO collaboration

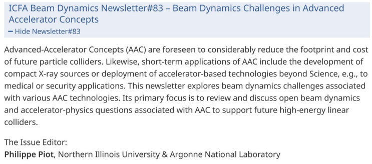
Abstract
This document provides additional information to support the ALEGRO proposal for R&D relevant to an Advanced Linear International Collider, ALIC, based on high gradient acceleration concepts.

LWFA



Leemans & Esarey Phys. Today (2009)

https://arxiv.org/pdf/1901.10370.pdf

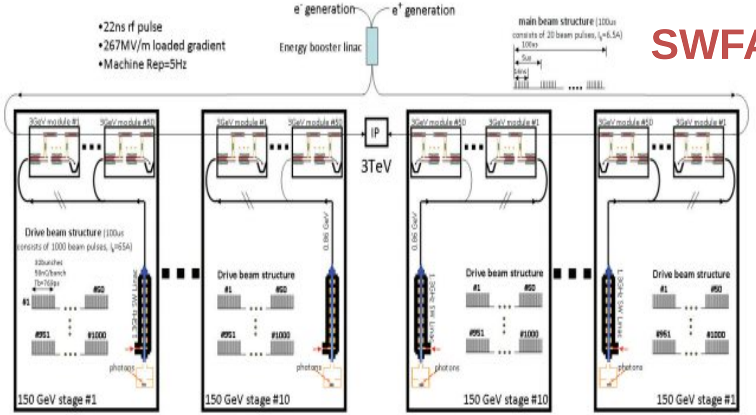

ICFA Beam Dynamics Newsletter#83 – Beam Dynamics Challenges in Advanced Accelerator Concepts

– Hide Newsletter#83

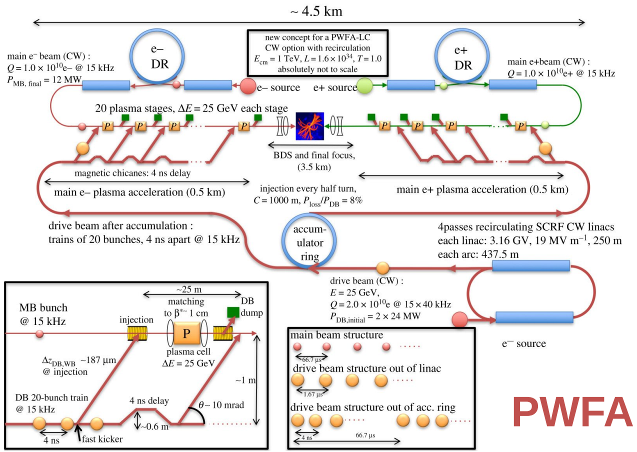
Advanced-Accelerator Concepts (AAC) are foreseen to considerably reduce the footprint and cost of future particle colliders. Likewise, short-term applications of AAC include the development of compact X-ray sources or deployment of accelerator-based technologies beyond Science, e.g., to medical or security applications. This newsletter explores beam dynamics challenges associated with various AAC technologies. Its primary focus is to review and discuss open beam dynamics and accelerator-physics questions associated with AAC to support future high-energy linear colliders.

The Issue Editor:
Philippe Piot, Northern Illinois University & Argonne National Laboratory

JINST special issue: ICFA Beam Dynamics Newsletter#83



SWFA



PWFA

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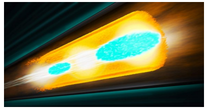
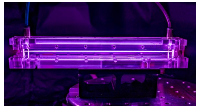
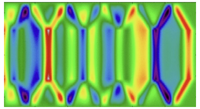
OUTLOOK

- **WFA has made significant progress over the last decade:**
  - Most of the beam parameters and building block required for a linear-collider have been demonstrated individually.
  - Reliable operation achieved and FEL lasing demonstrated.
  - Accelerator test facilities available at national laboratories are critical to WFA research.
  - Exciting opportunities for training of early-carrier scientists.
- **Exciting research opportunities (and challenges) remain before deploying WFA in a linear collider:**
  - To support the design of WFA-based colliders, several accelerator test facilities will require upgrades
  - Several planned/proposed “steeping-stone integrated” facilities to demonstrate performances required for a linear collider with physics potential (e.g. FEL farms, NLQCD).
  - Need stronger connections with HEP theorists to explore possible design options for a WFA-based linear collider.