Advanced Accelerators AF6

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AF6 Takeaway Messages

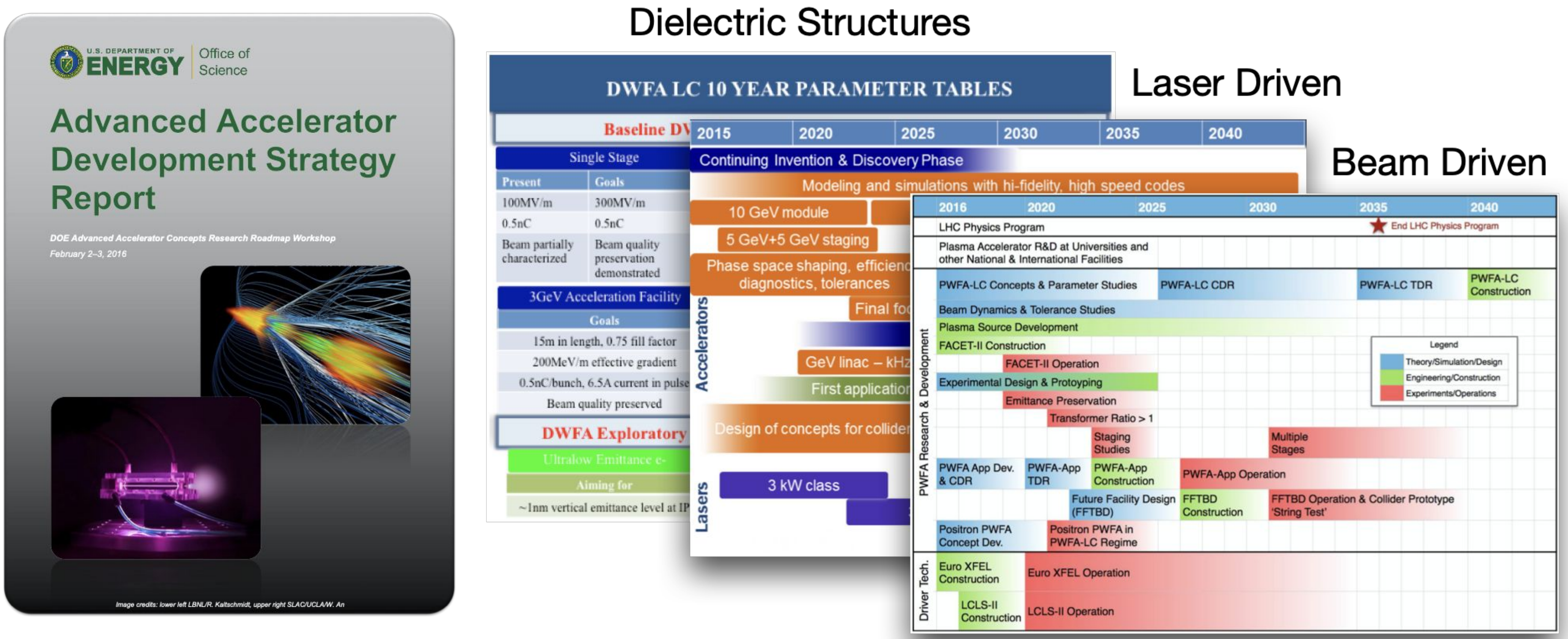
- Advanced accelerators in beam and laser driven structures/plasmas offer potential for compact, energy efficient future e-e+/gg colliders to 15 TeV range with few TeV/km geometric gradients
- Strong progress since last Snowmass assessing limits and with experimental demonstrations
  - Experimental results: 10 GeV class beams, beam loading & efficiency, plasma recovery, staging, high transformer ratio, positrons, and FEL-lasing demonstrating high beam quality
  - Concepts addressing: ion motion, synchrotron radiation, scattering, hosing and positron acceleration
- The next steps are a collider Integrated Design Study to advance overall technical maturity combined with strengthened R&D including test facilities and near term applications.
  - Includes: alignment and jitter tolerances, matching/coupling between many's of stages, optimized BDS and Final focus
  - Stepping stones leading to a collider demonstrator and future colliders

Report draft:
https://drive.google.com/drive/folders/1T3dvN43AokoLA41Wq8Ioe6e56fRcQBqr

Comments:
https://docs.google.com/document/d/1MXCTfE0cEpHokWTaydKmxqOaMSyQTJTNebTYBsZVPG8/edit

2016 Advanced Accelerator Development Strategy guides effort towards colliders, near term applications

- Roadmaps developed following Snowmass 2013 and ensuing HEPAP sub-panel
- Community representatives organized workshops and worked with DOE HEP to define roadmaps for three AAC technologies: LWFA, PWFA and SWFA
- Similar efforts have followed in Europe and US Roadmaps are being revisited as part of Snowmass 2021



AF6: Coordination meetings

- July 2020 Weekly AF6 meetings initiated
- August 2020 LOIs submitted
- September 2020 AF6 Snowmass prep LOI Workshop
  - Discuss 71 submitted LOIs
  - Encourage collaboration to group into focussed set of contributed papers with coherent message
- October 2020 Community planning meeting
  - Topical interest groups formed focussed around contributed papers
- The long pause…(but connected to ES/LDG process)
- December 2021 AF6 Contributed Paper Planning Meeting
  - Scheduled review for each paper in coming weeks
- February 2022 AF6 Review of all Contributed Paper Dafts
- July 2022 Pre-Snowmass review of AF6 Summary

- Snowmass in Seattle

Snowmass 2021

https://snowmass21.org/accelerator/advanced/start#white_paper_coordination

- In addition:
- Positron polarization
- AAC Agora
- e-e+ Collider Forum
- Cross Frontier Workshops with EF-TF-AF#
- ITF
- …

It's been a long and busy couple years!

AF6: Contributed Papers & Interest Groups

Theme	POC(s)
PASAIG (multiple papers: PWFA, LWFA, SWFA)	E. Esarey, W. Mori, C. Schroeder, J. Power, C.Jing, N. Vafaei-Najafabadi
(GARD) Beam Test Facilities - AF1	J. Power
Laser Drivers	L. Kiani, T. Zhou
BDS/IP Issues for Advanced Concepts	S. Gessner
Near term applications of Advanced Accelerators	J. Van Tilborg and C. Emma
Novel Electron Sources - AF7	M. Fuchs
Polarized positron generation - AF7	P. Musumeci
Laser Driven Structures	J. England
Nanoplasmonic accelerator	A. Sahai
Channeling based acceleration	S. Corde

To other Topical Groups:

- AF4 white paper integrating all elements of collider for plasmas/structures, possibly others (separate format)
- AF1 facilities paper (John P, from GARD facilities paper)
- AF7/AF3 polarized positrons (P. Musumeci)
- ITF input (input done, processing)
- FNAL site filler, ILC extension using AF6 tech. CCC
- Applications/industry, computing, environment…

https://snowmass21.org/accelerator/advanced/start

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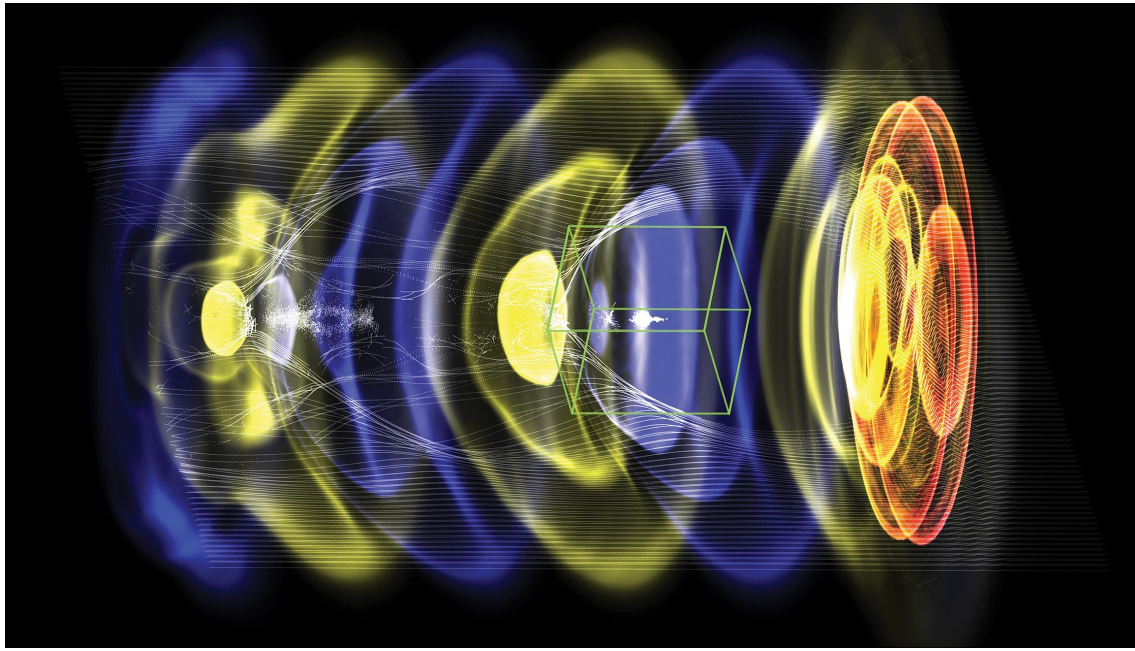
This presentation: highlights with representative report text

Advanced plasma and structure based accelerators: High gradients offer potential from TeV to many TeV

- Ultrahigh fields 1-100 GV/m
  - Beam generation, acceleration and focussing
  - Smaller linacs, smaller footprint, lower cost
- Ultrashort bunches 10 fs – 1 ps
  - Reduced beamstrahlung, high-luminosity/power
- Rapid accelerator R&D progress in last decade
- Compact colliders: polarized e+e-, gamma-gamma
- Photon sources for applications in medicine, industry
- Accelerator Frontier 6
- International Committee for Future Accelerators
- European LDG planning expert panel, report

Intense laser and particle beam driven plasmas or structures can circumvent current acceleration limits

Report draft:
https://drive.google.com/drive/folders/1T3dvN43AokoLA41Wq8Ioe6e56fRcQBqr
Comments:
https://docs.google.com/document/d/1MXCTfE0cEpHokWTaydKmxqOaMSyQTJTNebTYBsZVPG8/edit

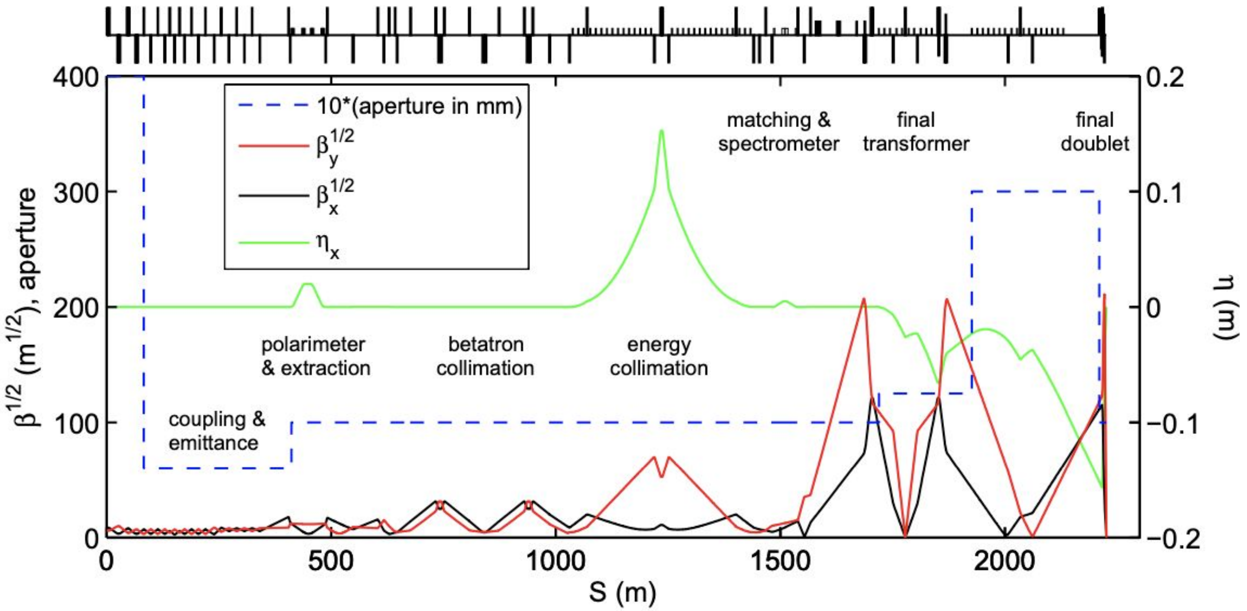


Example: a laser or particle beam (red) drives a density wave (blue to yellow) in plasma, accelerating electrons (white) with fields of order 10 GeV/m

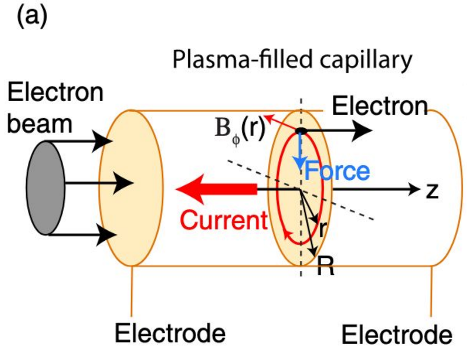
Interaction point beam delivery: strong focusing potential

- BDS system includes diagnostic sections and collimation sections in addition to the Final Focus and Machine-Detector Interface.
- The Final Focus uses the local chromatic correction in the final doublet.
- Novel chromatic correction techniques and strong focusing from plasma lenses could be used to reduce beam spot and BSD length
    - Details: S. Gessner et al., Snowmass Contributed Paper

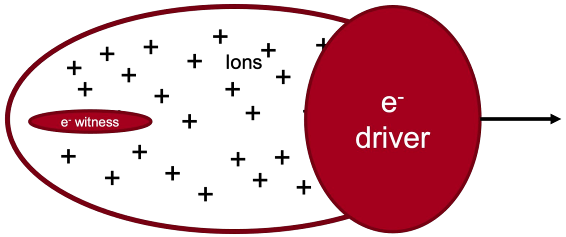
ILC BDS



Active Plasma Lens



Passive Plasma Lens



AF6 highlighted renewed interest in applying AAC technologies to many collider sub-systems

Advanced concepts offer path to increased luminosity / power

- Short beams decrease beamsstrahlung. Figure of merit: (luminosity)/(wall-plug power)

classical beamstrahlung regime (Y<<1):

$$\frac{\mathcal{L}}{P_{\text{wall}}} \approx \frac{1}{8\pi\alpha r_0}\frac{\eta N_\gamma}{\sqrt{s\sigma_y^*}}$$

Note: beam disruption less severe for ultra-short beams

quantum beamstrahlung regime:

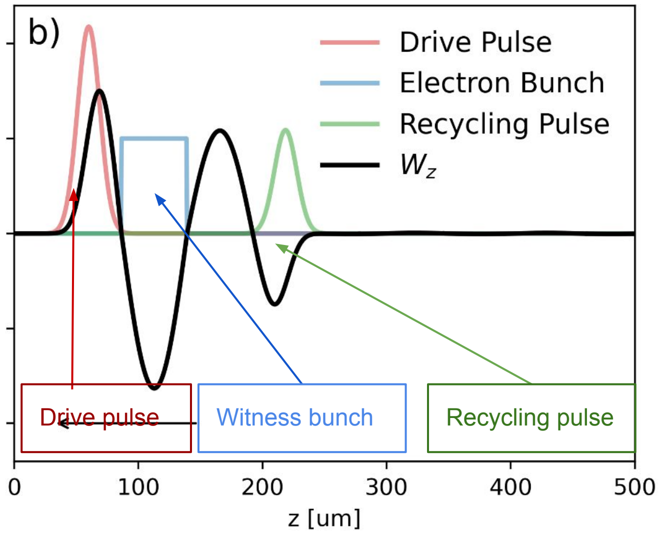
$$\frac{\mathcal{L}}{P_{\text{wall}}} \approx \frac{\sqrt{5}}{16\pi\alpha^2\sqrt{3r_0}}\frac{\eta\sqrt{\gamma N_\gamma^3}}{\sqrt{s\sigma_y^*}}\frac{1}{\sqrt{\sigma_z}}$$

Plasma-based injectors produce ~nm normalized emittance

AAC linacs accelerate short beams (tens of um)

- Energy recovery using recycling pulse
  - Particle beam energy (applicable to all colliders)
  - Wake energy, drivers (applicable to wakefields driven by beams and lasers in plasmas, structures)
- Re-use pulses or recover energy in RF or PV systems

- Potential 2x or more reduction in energy use
  - *Detail: M. Turner, Snowmass CF workshop*



Opportunities to reduce power consumption in-line with heightened environmental awareness

Advanced plasma and structure based accelerators: High gradients offer potential from TeV to many TeV

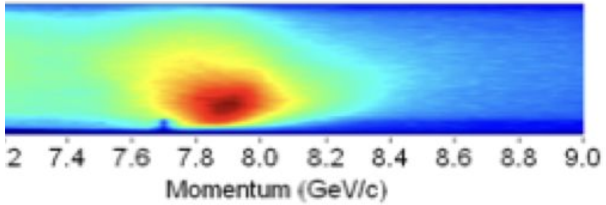
Efficiently harnessing the interaction of charged particles with extremely high electromagnetic fields at very high frequencies is the key to reaching ultra high gradients (GeV/m and beyond) and hence to reducing the dimensions, $C0_2$ footprint, and costs of future high energy physics machines, with the potential to reduce power consumption and offer e+e- and $\gamma - \gamma$ machines to and beyond 15 TeV energies. In addition to proven high gradient and ultra-bright beam generation, these systems have the potential for short beams to increase luminosity per unit beam power, for practical energy recovery to extend the reach of high energy physics, and for fast cooling. Techniques range from laser and beam driven plasma and advanced structure accelerators to advanced phase space manipulations and generation of beams with extreme parameters [1]. Recognizing this promise the last Snowmass and P5/HEPAP recommended, and DOE developed with the community, an organized Advanced Accelerator Development Strategy, and work has been aligned to it [2].

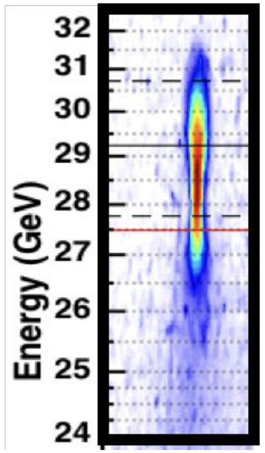
Rapid experimental progress since last Snowmass

LWFA: 8 GeV **energy gain** in 20 cm stage using BELLA PW laser

PWFA: 9 GeV in 1.3 m using SLAC at FACET

New: 12 GeV from LWFA at U Texas (submitted)

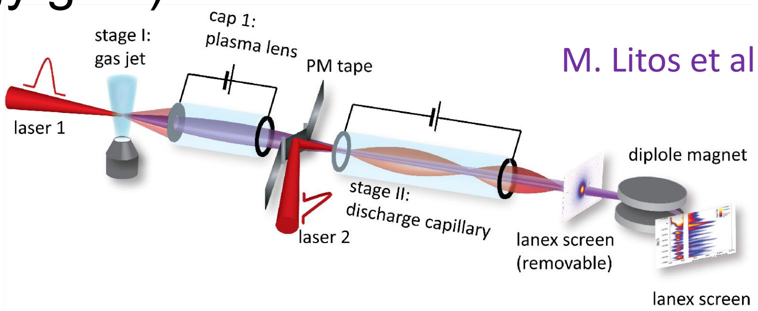




A. J. Gonsalves et al. PRL (2019)

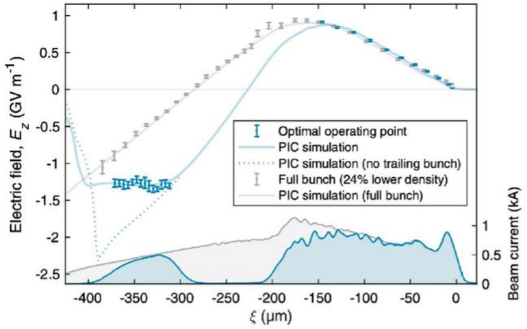
M. Litos et al. PPCF (2015)

Proof-of-principle **staging** of LWFAs (~100 MeV energy gain) using high gradient plasma-lenses



S. Steinke et al. Nature (2016)

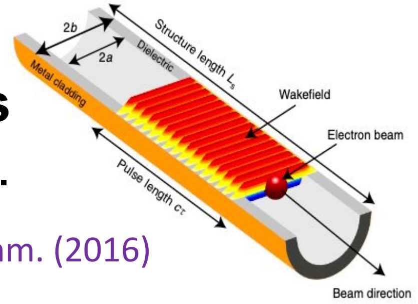
Optimized beam loading in PWFA enables uniform, **high-efficiency** acceleration.



42% transfer efficiency
with 0.2% energy spread

C. A. Lindstrom et al. PRL (2021)

Demonstration >1**GeV/m gradients** SWFA dielectric structures.



B. O'Shea et al. Nature Comm. (2016)

Plasma recovery at high rep-rate

R. D'Arcy et al., Nature (2022)

Demonstration 0.5 **GW power** SWFA structures.

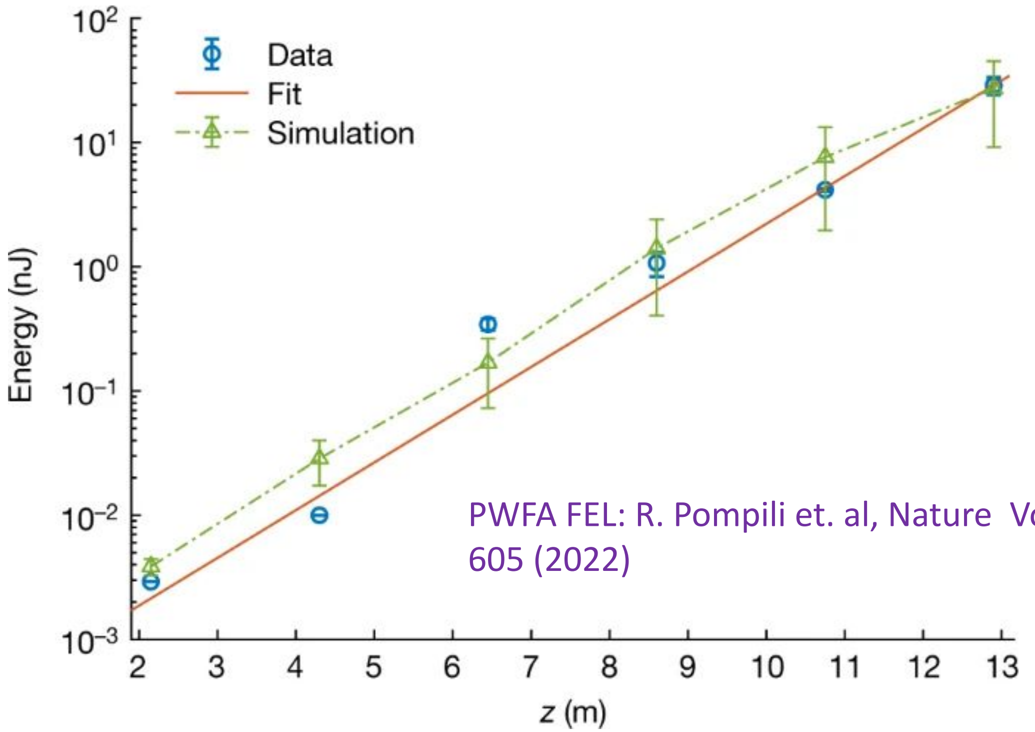
Driver Technology:

Superconducting XFELs, New laser technology (fibers, Thulium) promise high average power at high efficiency

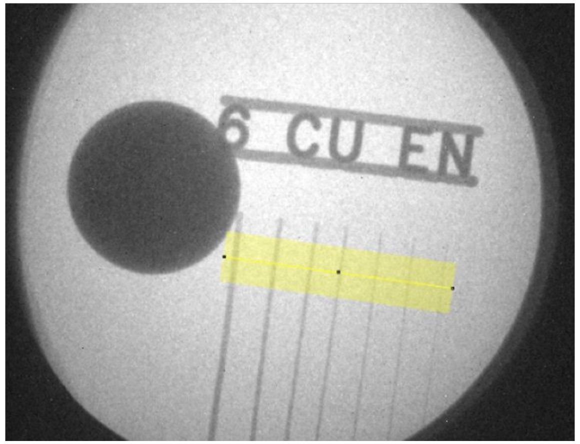
Also: positron PWFA, hollow channels for low emittance growth, 0.1 micron emittance

Plasma acceleration based light sources

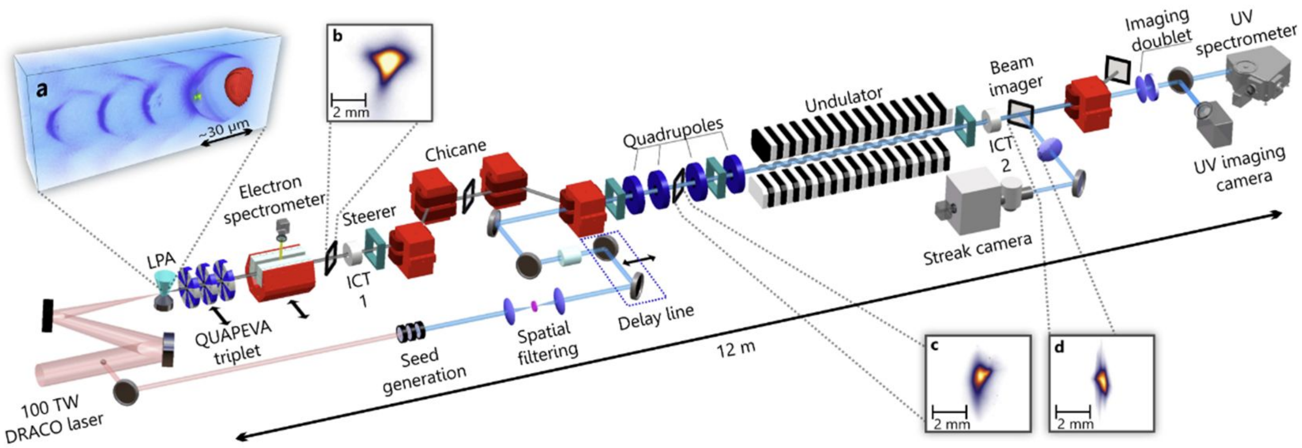
LWFA FEL: W. Wang et. al, Nature Vol 595 (2021)



PWFA FEL: R. Pompili et. al, Nature Vol 605 (2022)



LWFA Thomson precision imaging



Seeded FEL: M. Labat et al.: DOI:10.21203/rs.3.rs-1692828/v1

High fields enable ultra-bright sources

- Conventional injector brightness constrained by transverse energy of emitted electrons and space charge forces

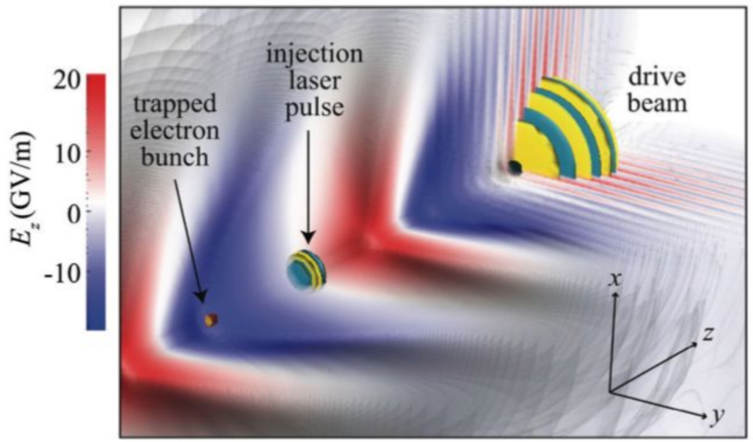
- GeV/m plasma gradients transform electron brightness
  - Rapid acceleration + shielding reduce space charge effect
  - Primary limit due to transverse momentum

- 0.5 GeV/m gradients in SWFA Two Beam Accelerator gun
  - Rapid acceleration, ~10nm emittance
  - Ultralow dark-current

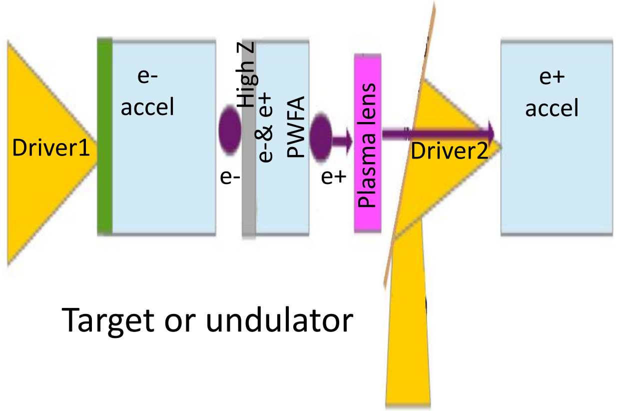
- Control transverse momentum via ionization/structure
  - multi kA, 100 pC and 50 nm emittance beams, path to 10nm class directly from plasma injector
  - *Reduces/eliminates cooling and conditioning needs*

- Positron sources; polarization using undulators or lasers
  - Polarized positrons, rapid acceleration, capture and cooling

Multi-beam control of emittance



Wakefield positron sources
Compact high-E and capture



Potential to extend performance of nearer-term LC (e.g. ILC, CCC) & future AF6

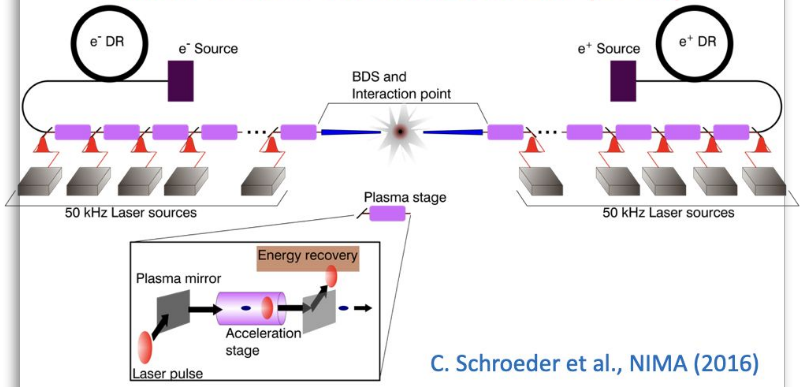
Rapid experimental progress since last Snowmass

In the last decade advanced accelerator research has seen tremendous progress including the demonstration of multi-GeV acceleration in a single stage [3, 4], positron acceleration [5], efficient loading of the structure [6, 7], the first staging of plasma accelerators [8], demonstration of beam shaping to improve efficiency in plasmas [9] and structures [10], high gradient structures [11] and greatly improved beam quality [12, 13] which recently culminated in the spectacular first demonstrations of laser-driven and beam-driven plasma based FELs [14, 15].

Wakefield-based Colliders: Staged High-gradient Accelerators with Geometric Gradients 0.2 - 2 GeV/m

- Collider designs have been developed to guide research priorities (efficiency, staging…)

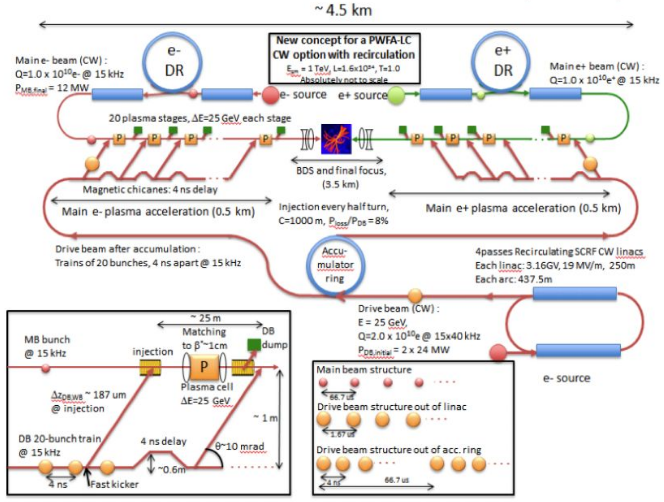
Laser-driven Plasma Accelerator (LWFA)



C. Schroeder et al., NIMA (2016)

5 GeV/stage; Geometric gradient: 2.3 GV/m

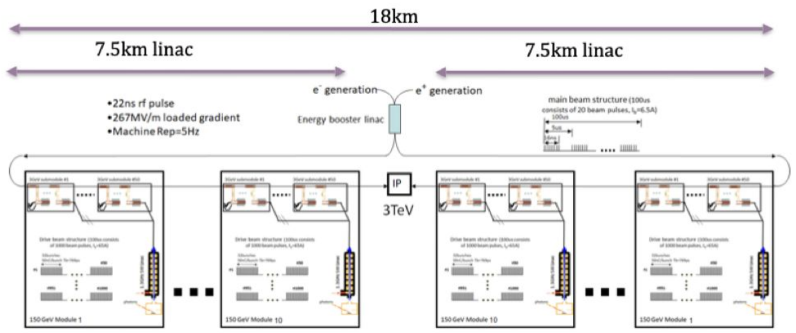
Beam-driven Plasma Accelerators (PWFA)



25 GeV/stage; Geometric gradient: 1 GV/m

E. Adli et al., arXiv:1308.1145 (2013); Chen et al., arXiv2009:13672

Structure Wakefield Accelerator (SWFA)



0.267 GeV/stage; Geometric gradient: 0.2 GV/m

https://accelconf.web.cern.ch/ipac2013/papers/tupea088.pdf

Next step – integrated design studies

Assessment of limits indicates potential for 15 TeV-class

- AAC community has addressed potential limits of high-gradient linac technology
  - Shaped bunches can be used to efficiently accelerate beams without energy spread growth
  - Ion motion induced by dense beams can mitigate transverse hosing instability
  - Scattering in plasma mitigated by strong plasma focusing
  - Energy spread from synchrotron radiation in plasma limited by small beam emittances
  - Laser and beam energy recovery may be used for improved efficiency

- Additional technical challenges require R&D
  - 100's of stages: Beam matching / coupling between including efficiency ≥ 99%
  - Small accelerating structures place challenging alignment and jitter tolerances
  - Plasma-based beam delivery system and final focus

- Wall-plug power (operating costs) will limit energy reach of e+/e- linear colliders based on AAC
  - Beamstrahlung limits bunch charge and luminosity requirements increase required power:
  - Short beams and low emittance reduce power requirements (LOIs inc. 37, 190)
  - High gradients could enable practical energy recovery

$$P_{\text{beam}} \propto \gamma^{5/2}\sigma_z^{1/2}\sigma_x$$

AAC technology are capable of 15-TeV-class e+e- linear collider parameters

Collider potential to 15+ TeV & re-using near-term facilities

- Similar parameter ranges accessible to each technology: coordinated example assembled
  - TeV-class established as part of 2016 AARD report, extended to 15 TeV
  - Next step for AF: integrated design study, self consistent and including tradeoffs

- Sequence of collider options available to the 15 TeV class: polarized e+e- or gamma-gamma (with ITF)
  - New concepts continue to emerge that extend performances
  - Potential to re-use infrastructure of nearer-term LC (e.g. ILC, CCC) to enable many TeV

Example: similar sets for beam driven and structure

Laser-plasma linear e-/e+ collider		3 TeV
Beam energy	TeV	1.5
Particle number (1E9)		1.2
Beam power	MW	13
Luminosity (1E34)	cm-2 s-1	10
Transverse. beam sizes at IP, x/y	nm	10 / 0.5
IP beta function, β^*	mm	0.1
RMS bunch length	micron	8.5
Repetition frequency	kHz	47
Time between collisions	microsec	21
Beamstrahlung photons/e-		1.7
Length (2x main linac tunnel)	km	1.3
Facility site power (2 linacs)	MW	315

LWFA parameters: 1 um laser wavelength, 10^{17} cm^{-3} plasma density

Assessment of limits indicates potential for 15 TeV-class

At the same time, solutions for potential collider issues have identified demonstrating that in principle the required nm-class emittance can be preserved (addressing potential limits due to scattering, hosing, and radiation), and that shaped bunches can be used to efficiently accelerate beams without energy spread growth. Driver technologies (SRF linacs, high average power lasers) are developing consistent with the luminosity and efficiency needs of future colliders. Conceptual parameter sets for colliders have been developed for e+e- and $\gamma\gamma$ colliders at a range of energies, and current evaluations indicate they present competitive options [16] with potential for future cost reduction. This progress has been supported by the rapid development of high performance PIC codes, and development will continue to require the leading edge of supercomputing.

Strong role in workforce development

Over 1000 research papers published annually in advanced and novel accelerators.

Spawning numerous new ideas, concepts, techniques that will help bring a future advanced accelerator based collider to fruition.

Attracts students and new researchers to the field,

Provides opportunities that are important for involving more diverse communities,

Support the goals expressed in the CEF papers for diversity, equity and inclusion.

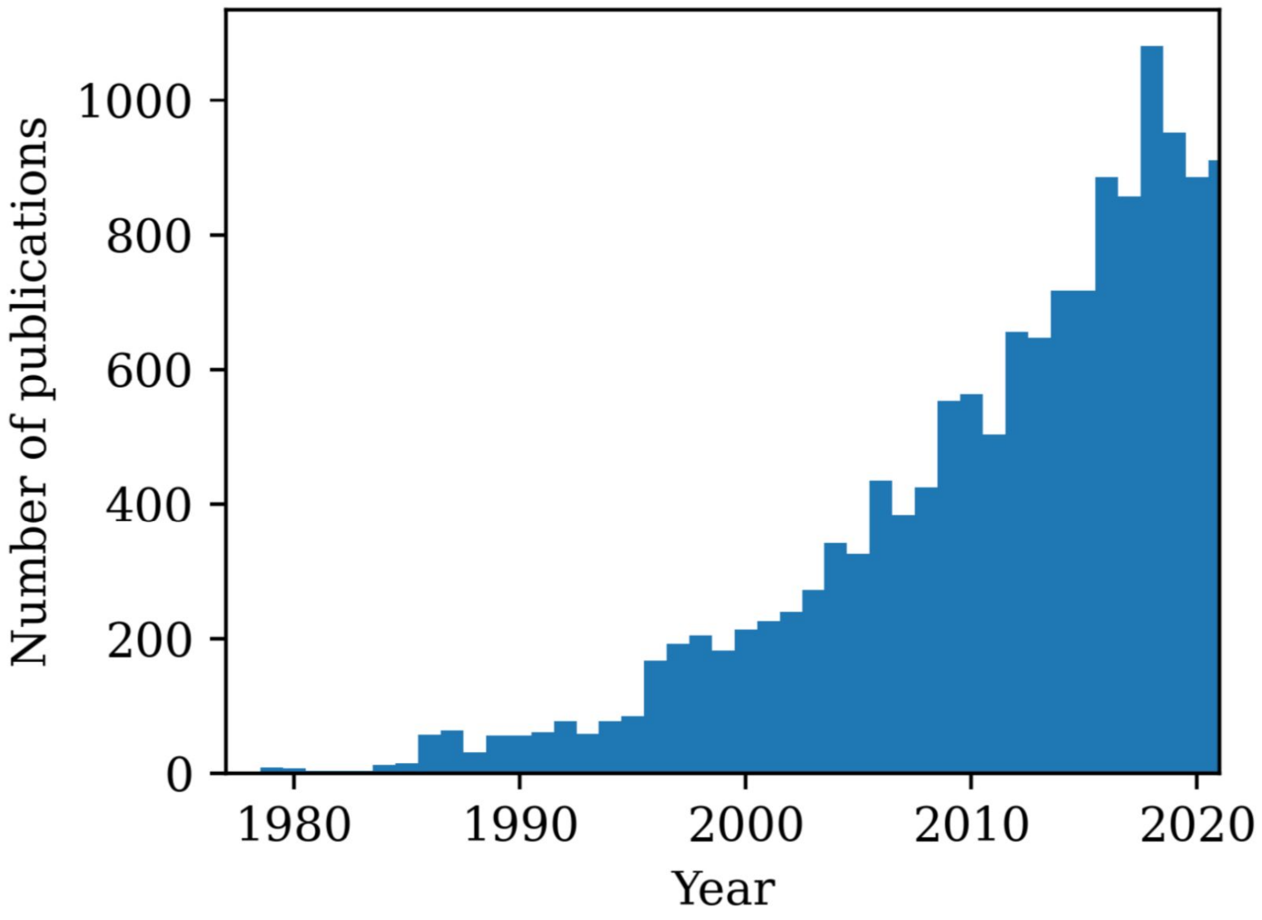
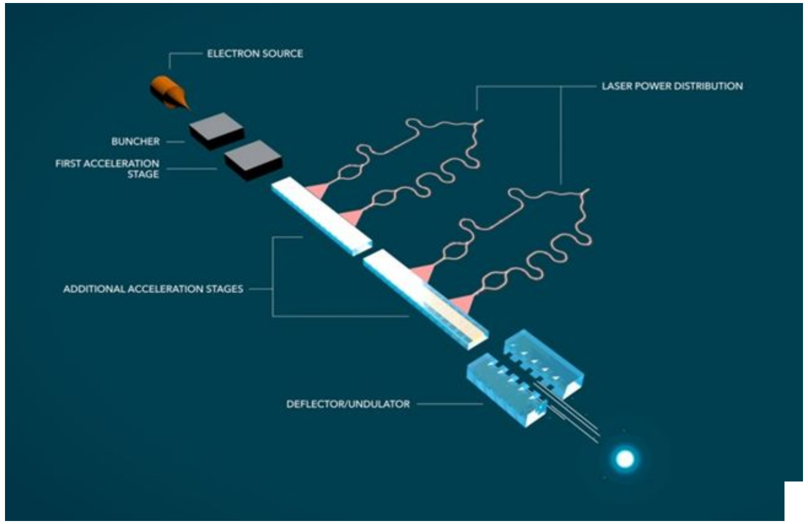


Figure 1: Example strong research, showing the number of publications per year as obtained from a Google Scholar search on articles containing all of the following keywords: “laser+plasma+wakefield+accel*”.

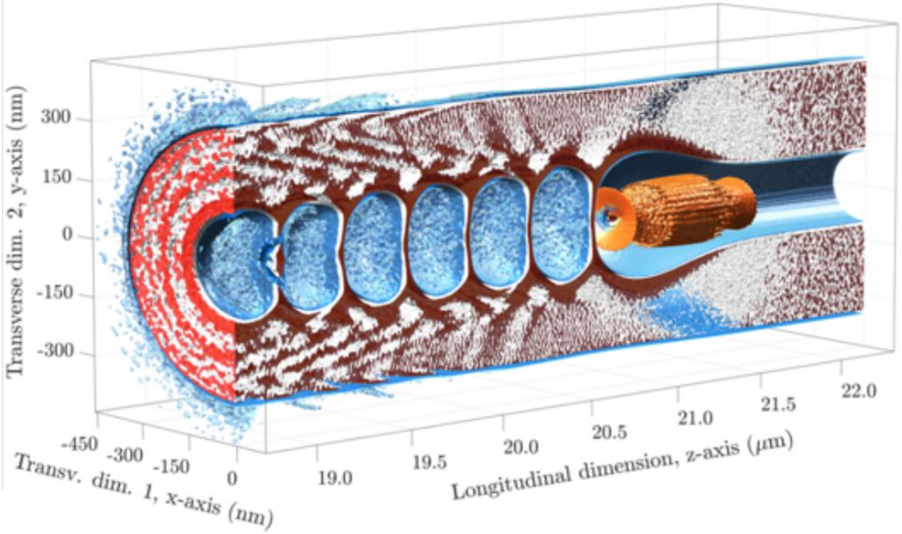
Innovation in concepts for high gradient acceleration

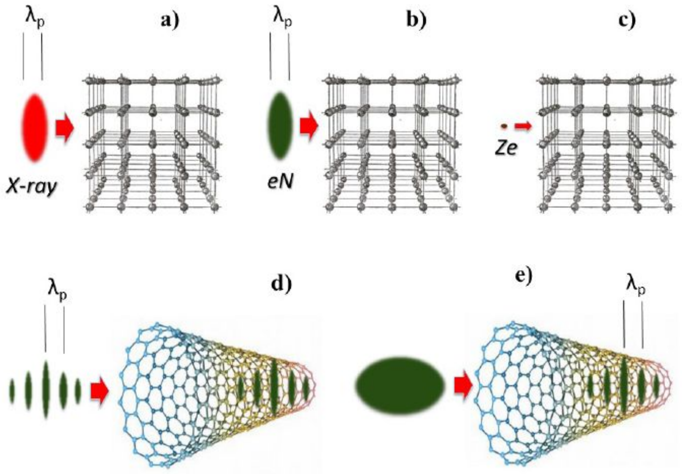
Other new techniques continue to emerge and be developed ranging from laser driven structures to plasmonics and channeling demonstrating the rich potential of future accelerators to extend the reach of physics.

Laser driven structures: Accelerator-on-a-Chip



Plasmonic modes for ultrahigh gradient (approaching PV/m)





Structured plasma.
Channeling-based accelerators

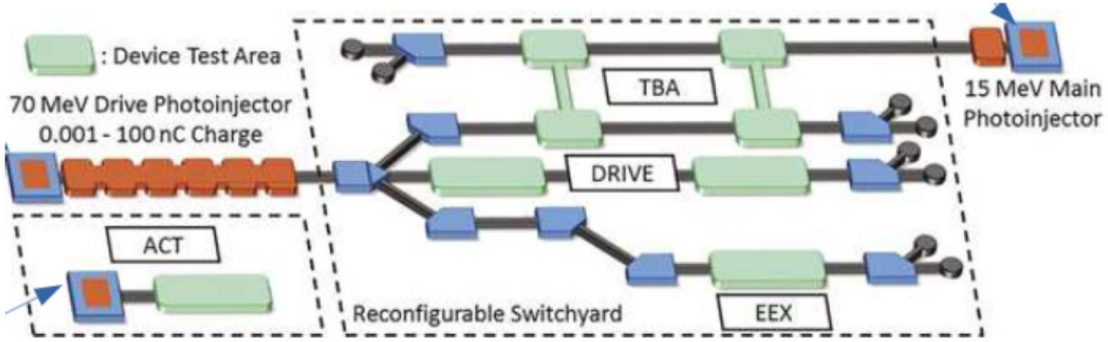
Innovation in new concepts, strong role in workforce

While advanced accelerators in plasmas and structures continue to advance towards collider and near term applications, innovative concepts such as nanoplasmonics and laser-driven structures continue to emerge offering the potential for greater reach, new accelerator components, and near term applications in the future. In this context, advanced accelerator R&D and facilities serve all novel accelerator research. Furthermore, they play a critical role in accelerator and beam workforce development and diversity since they allow hands-on training with strong publication (over 1000 papers/year) for the next generation of accelerator scientists from more diverse communities who are often attracted to the field by the scientific novelty and rich physics of advanced accelerators.

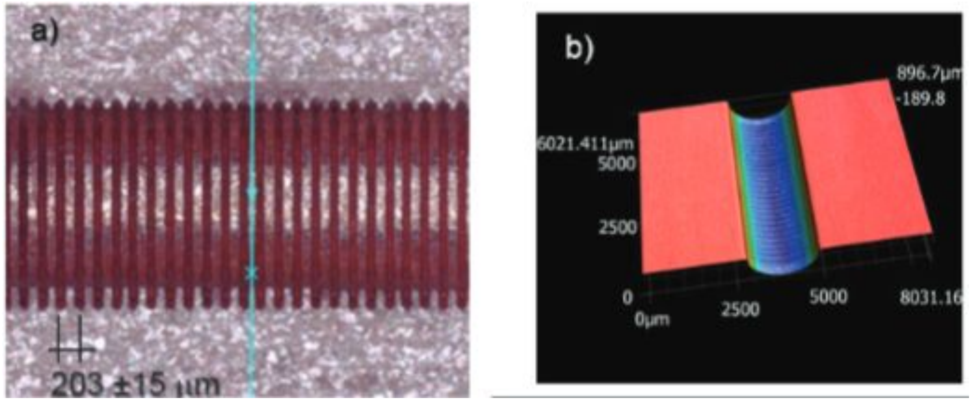
AAC Beam Test Facilities play a leading role

- Circa 2025, anticipate high-level demonstrations at existing beam test facilities:
  - Laser driven staging of two 5 GeV-class cells with high efficiency @ BELLA
  - Beam driven demonstration of 10 GeV single stage with mm-mrad emittance, percent energy spread and high-efficiency @ FACET-II
  - Plasma repetition rate limits characterized @ FLASHForward, FACET-II
  - Demonstrate potential for intermediate applications (pre-collider)
  - 500MeV SWFA demonstrator module @ AWA

- Near term applications will establish technology, and benefit future colliders:
  - Compton MeV photons, FELs, nQED, injector…
  - societal benefit, increase HEP investment return

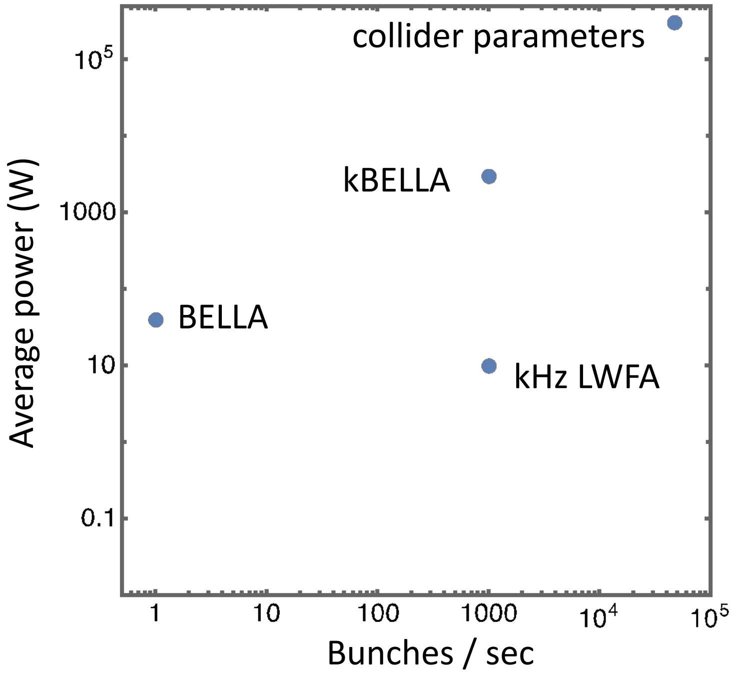


Argonne Wakefield Accelerator test facility

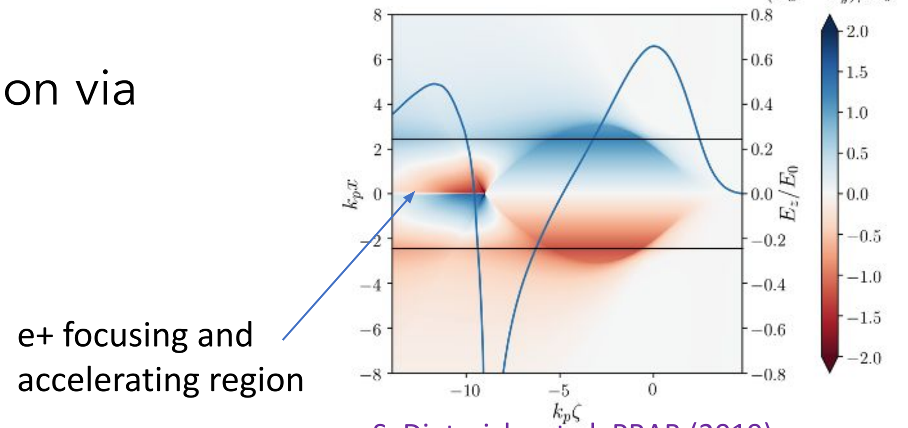


AAC facility next steps will advance technology and test key remaining parameters

- Rapid investment in Europe, Asia, incl. EuPRAXIA ($600M-class)
  - US R&D, facility base creates leadership opportunities
- Positron acceleration R&D
  - *Technical challenges:* plasma acceleration of stable, high-quality e+ beams, with high efficiency (comparable to e-)
  - *FACET-II upgrade*: plasma-based positron acceleration experiments/tests (e.g., plasma columns or hollow channels)
- Staging of two modules and multiple-driver/injector beams
  - *BELLA 2nd beamline:* staging; future positrons & injectors
- High-average power and high repetition rate plasma accelerators:
  - *Technical challenges*: targetry at repetition rate, heat deposition and management (~kW/cm), structure durability
  - *kBELLA project*: kHz, J-class laser. Technology available; precision via active feedback, applications on collider roadmap
- Integrated submodule of TeV SWFA design:
  - GW rf power generation and sustainable 0.5GV/m acceleration
  - Over 50% of RF-to-beam efficiency with shaped main beam.
  - 3GeV demonstrator in AWA-II High-Energy Upgrade.



Wake excited in plasma column

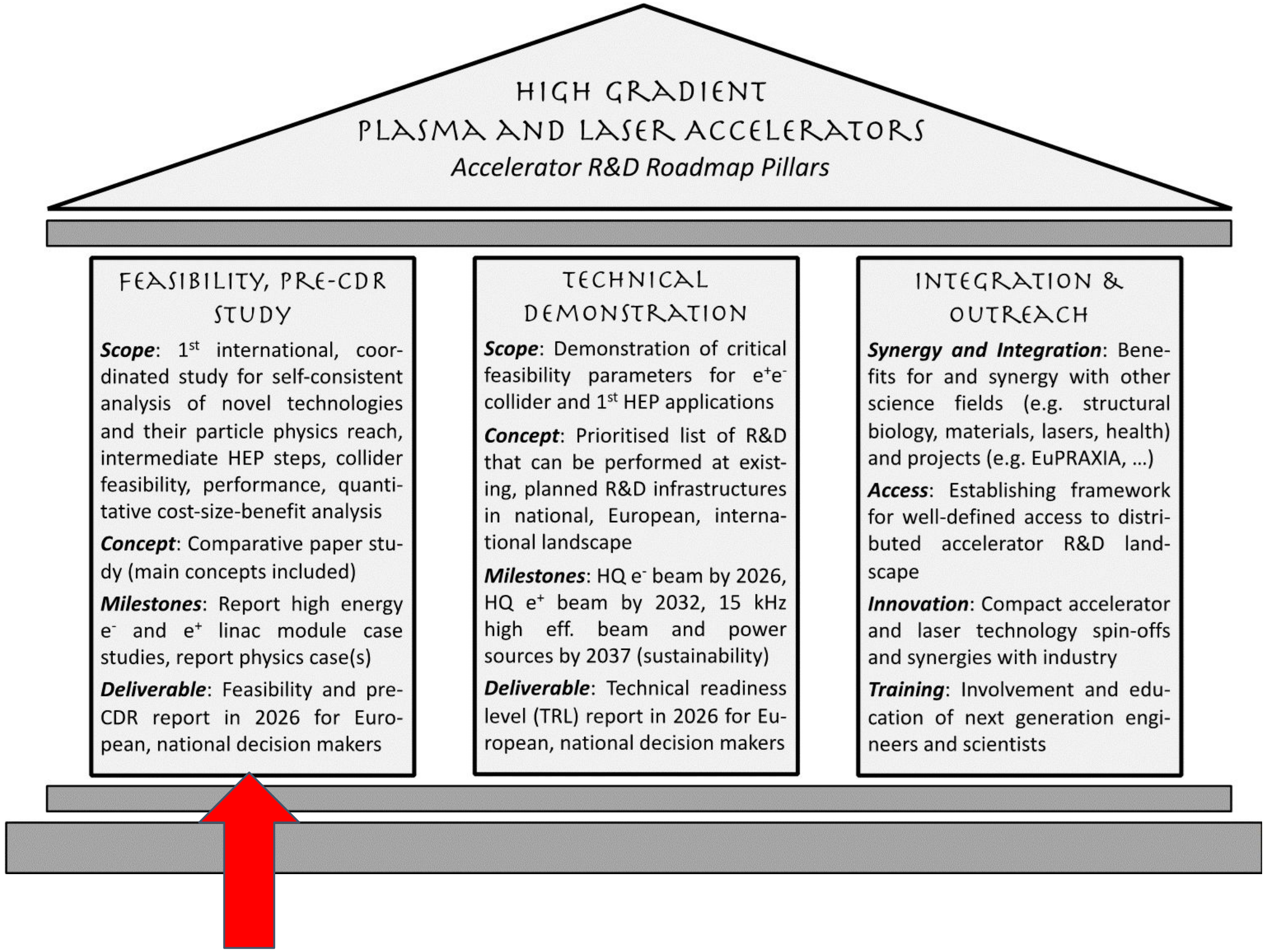


S. Dieterichs et al. PRAB (2019)

Collider potential to 15+ TeV

While recent results indicate that the main building blocks of future advanced accelerators are workable and promising, significant development is still required. There are still several challenges to be addressed including how to achieve the high wall-plug efficiency and high repetition rates needed to fulfill future collider luminosity requirements, how to preserve small energy spreads and beam emittance over many acceleration stages and, for plasmas, efficient positron acceleration.

Integrated design study and near term applications



Strong overlap of AAC with compact light sources

European Strategy for Particle Physics Roadmap for Accelerator R&D highlights the need for pre-CDR study

Priority research directions

With the goals of addressing these long standing questions and realizing the promise of advanced accelerators, in addition to a strengthened R&D program to solve outstanding critical issues, two new research directions can be identified. An integrated design study is needed to unite all the various elements in AAC and offer a clear and actionable R&D path towards a future collider. At the same time, in order to increase the technology readiness level of advanced accelerators and provide a viable path to an AAC collider, the need is also clear to pursue nearer-term applications

At the same time, synergies with existing or near future colliders should be explored in the near term. The extremely high fields of advanced accelerator concepts could be used for transverse focusing of the beam, advanced phase space manipulations or particle sources.

Recommendations

Priority research should continue to address and update the Advanced Accelerator Development Strategy:

- Vigorous research on advanced accelerators including experimental, theoretical, and computational components, should be conducted as part of the General Accelerator R&D program to make rapid progress along the advanced accelerator R&D roadmaps towards an eventual high energy collider, develop intermediate applications, and ensure international competitiveness. Priority directions include staging of multiple modules at multi-GeV, high efficiency stages, preservation of emittance for electrons and positrons, high fidelity phase space control, active feedback precision control, and shaped beams and deployment of advanced accelerator in real-world applications.
- A targeted R&D program for a integrated design study of a high energy (1–15 TeV) advanced accelerator-based collider should be performed in coordination with international efforts detailing all the components of the system, such the injector, drivers, plasma source, beam cooling, and beam delivery system. This would set the stage for a future conceptual design report, after the next Snowmass.

Recommendations

- Research in near-term application should be recognized as essential to progress towards HEP goals. Mechanisms should be identified for HEP to pay close attention to and participate in research activities aimed at real-world deployment of advanced accelerators. The interplay and mutual interests in accelerators between HEP, BES, FES, ARDAP and other offices within DOE as well as cross-agency should be strengthened.

- Advanced accelerators should continue to play a key-role in workforce development and diversity in accelerator physics. University programs and graduate students greatly benefit from the scientific visibility of the advanced accelerator field. Access to user facilities for graduate students and early career researchers as well as formal and hands on training opportunities in advanced beam and accelerator physics should be continued and enhanced.

- Enhanced driver R&D is needed to develop the efficient, high repetition rate, high average power laser and charged particle beam technology that will power advanced accelerators colliders and societal applications.

Recommendations

- Support of upgrades for Beam Test Facilities are needed to maintain progress on advanced accelerator Roadmaps. These include development of a high repetition rate facility, proposed as kBELLA, to support precision active feedback and high rate; independently controllable positrons to explore high quality acceleration, proposed at FACET-II; and implementation of a integrated SWFA demonstrator, proposed at AWA.
- A study for a collider demonstration facility and physics experiments at an intermediate energy (c.a. 20–80 GeV) should establish a plan that would demonstrate essential technology and provide a facility for physics experiments at intermediate energy.
- A DOE-HEP sponsored workshop in the near term should update and formalize the U.S. advanced accelerator strategy and roadmaps including updates to the 2016 AARDS Roadmaps

AF6 Takeaway Messages

- Advanced accelerators in beam and laser driven structures/plasmas offer potential for compact, energy efficient future e+e-/gg colliders to 15 TeV range with few TeV/km geometric gradients
- Strong progress since last Snowmass assessing limits and with experimental demonstrations
  - Experimental results: 10 GeV class beams, efficiency & beam loading, plasma recovery, staging, high transformer ratio, positrons, and FEL-lasing demonstrating high beam quality
  - Concepts addressing: ion motion, synchrotron radiation, scattering, hosing and positron acceleration
- The next steps are a collider Integrated Design Study to advance overall technical maturity combined with strengthened R&D including test facilities and near term applications.
  - Includes: alignment and jitter tolerances, matching/coupling between many's of stages, optimized BDS and Final focus)
  - Stepping stones leading to a collider demonstrator and future colliders.

Report draft:
https://drive.google.com/drive/folders/1T3dvN43AokoLA41Wq8Ioe6e56fRcQBqr

Comments:
https://docs.google.com/document/d/1MXCTfE0cEpHokWTaydKmxqOaMSyQTJTNebTYBsZVPG8/edit