Advanced and Novel Accelerators for Colliders

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On behalf of the
Plasma and Advanced Structure Accelerators Interest Group

Snowmass EF Meeting, April 4, 2022

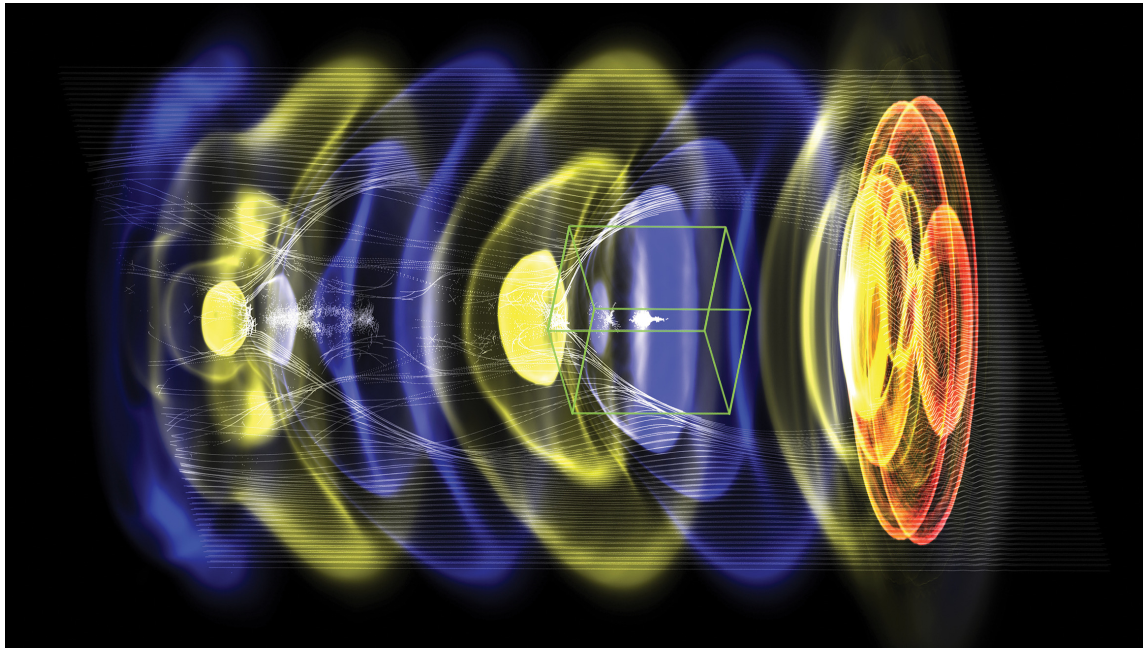
Advanced and Novel Accelerators (ANAs): Ultrahigh fields offer potential from TeV to many TeV

- Intense laser and particle beam driven plasmas or structures can circumvent current acceleration limits
- Ultrahigh fields 1-100 GV/m
  - Smaller linacs, lower cost
- Ultrashort bunches 10 fs – 1 ps
  - Reduced beamstrahlung, lower drive power
- Rapid accelerator R&D progress in last decade
  - High brightness, 10 GeV-class energies, staging, ultra-bright beams, fast cooling & focusing….
- Compact colliders: polarized e+e-, gamma-gamma
- Photon sources for applications in medicine, industry
- Strongly endorsed by European reports

Structure-based wakefield accelerator (SWFA)

Plasma wakefield accelerator (PWFA)

Laser wakefield accelerator (LWFA)



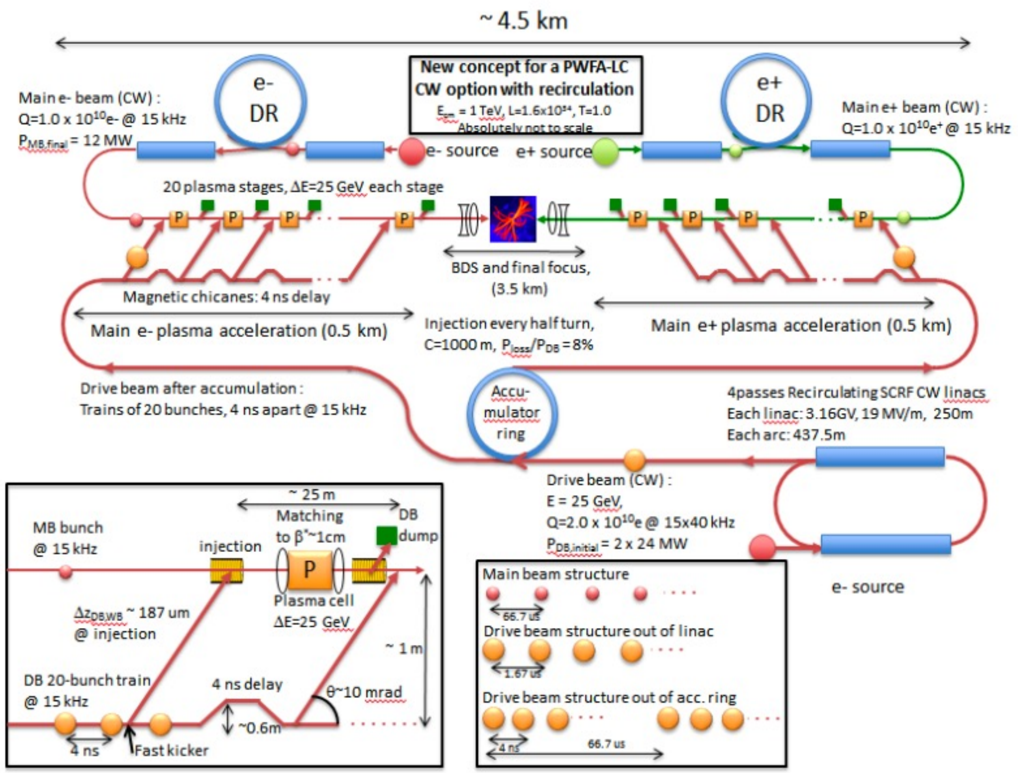
Example: a laser or particle beam (red) drives a density wave (blue to yellow) in plasma, accelerating electrons (white) with fields of order 10 GeV/m

Plasma-based colliders: staged plasma accelerators with >1 GV/m geometric gradients

- Preliminary designs (not integrated design studies) to outline a plasma collider and guide R&D

Beam-driven plasma accelerators (PWFA)

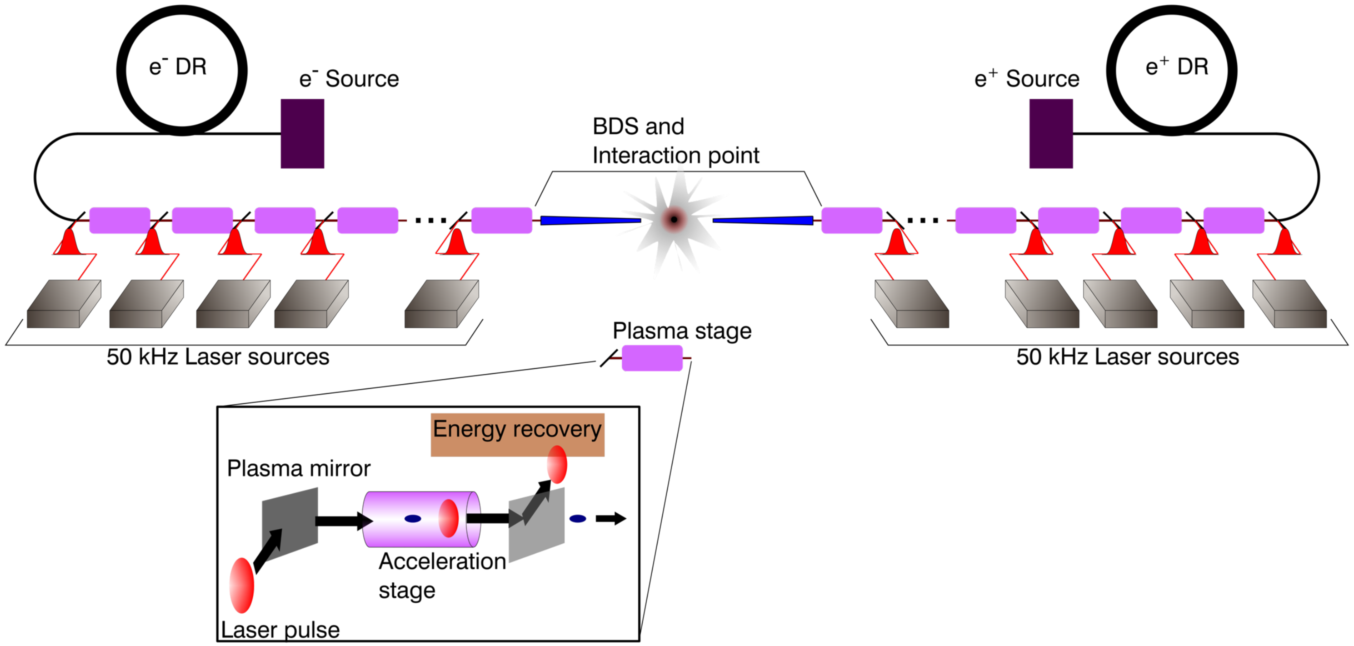
Figure 1: Layout of a 1 TeV PWFA Linear Collider



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

- Operating plasma density: 2×10^{16} cm^{-3}
- 25 GeV/stage; Geometric gradient: 1 GV/m

Laser-driven plasma accelerators (LWFA)

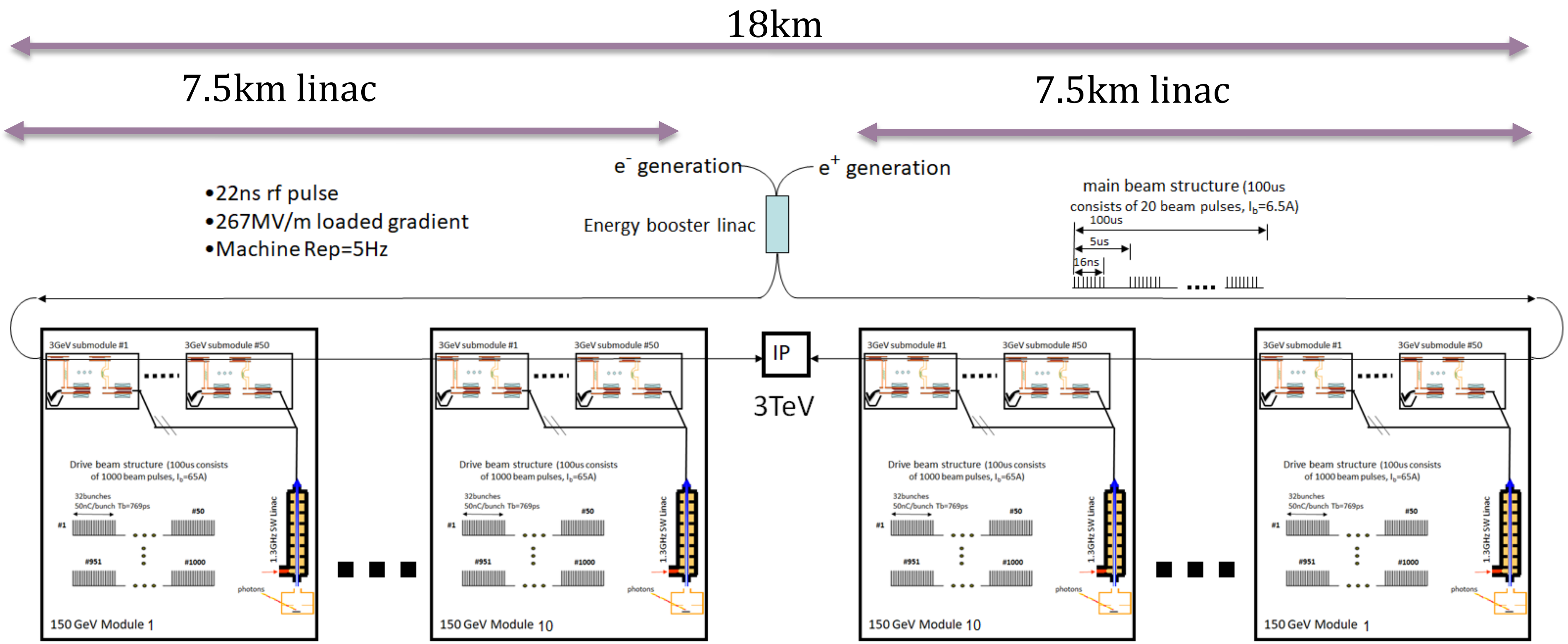


C. Schroeder et al., NIMA (2016)

- Operating plasma density: 1×10^{17} cm^{-3}
- 5 GeV/stage; Geometric gradient: 2.3 GV/m

SWFA – LINEAR COLLIDER STRAWMAN

3TeV 30MW beam power TBA



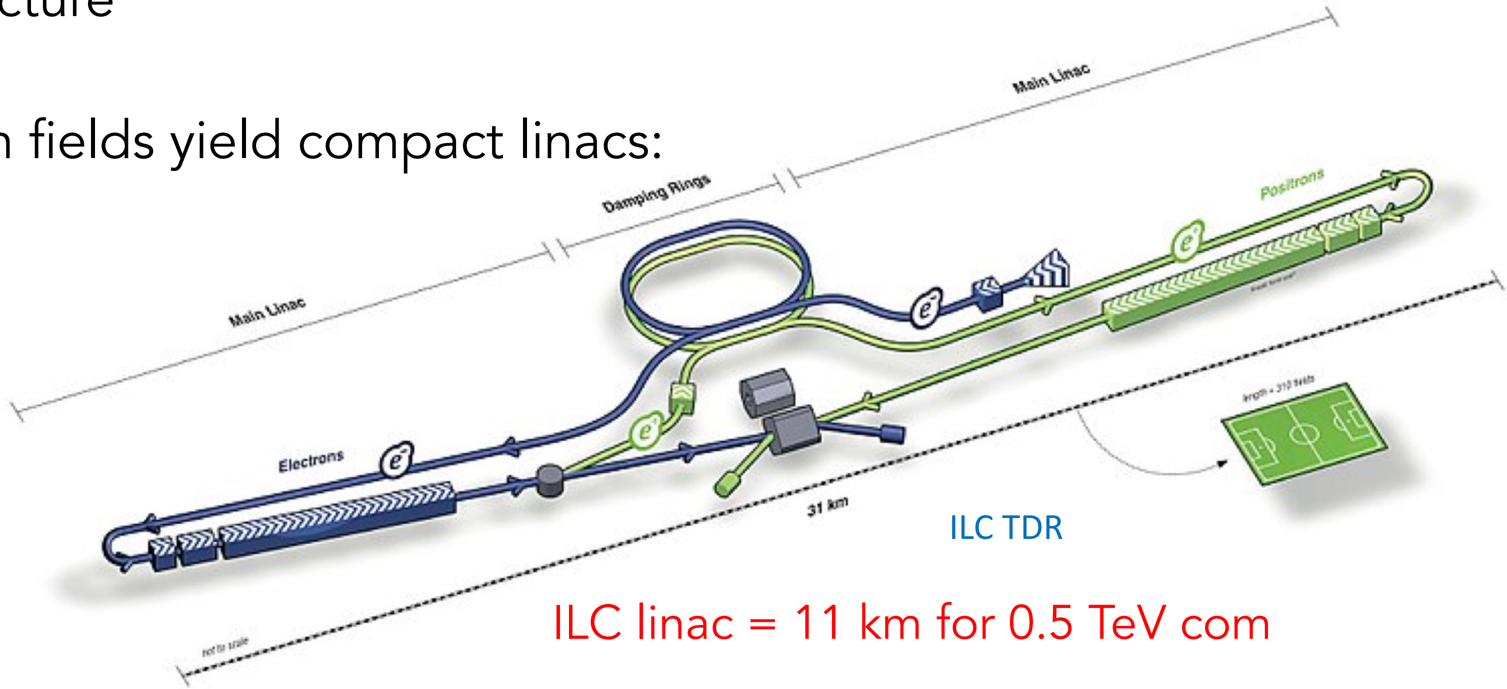
Based on scientifically mature and low cost SWFA Short Pulse TBA technologies

- Short rf pulse (**20ns**) for high gradient (**$e^+ e^-$ 200MeV/m of geological gradient**)
- Modular design →easily staged
- Wall plug efficiency **(~15%)**

Extending energy reach of existing LC facility

- Repurpose an existing (future) conventional RF linear collider facility
  - Reuse existing tunnels and infrastructure

- Advanced and Novel Accelerators: High fields yield compact linacs:
  - sub-km linacs for TeV com:
  - few km linac for 10 TeV com



ILC TDR

ILC linac = 11 km for 0.5 TeV com

- Example: ILC facility
  - Replace RF with plasma stages:
  - e.g., LWFA at 2.3 GV/m over 11 km yields 50 TeV com

- FermiLab site
  - Multi-TeV ANA collider possible

High energies (>10 TeV) accessible in conventional accelerator facility footprint

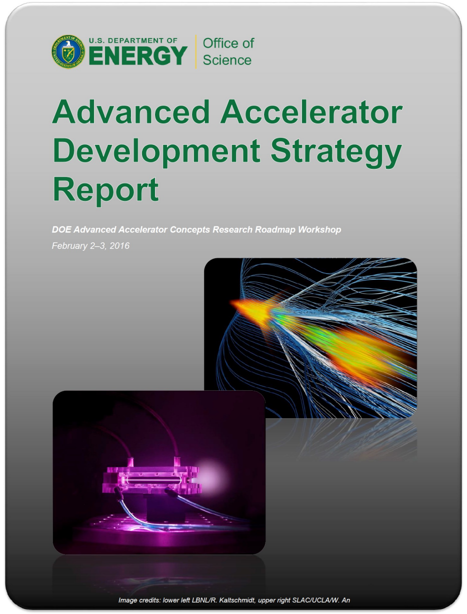
Collider studies establish accessible parameter sets

- Similar parameter ranges accessible to each technology: coordinated example assembled
  - TeV-class established as part of 2016 AARD report, extended to 15 TeV
  - Documented in Snowmass white papers
  - Potential to re-use infrastructure of near-term LC (e.g. ILC)
  - Next steps 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
  - New concepts continue to emerge that extend this potential

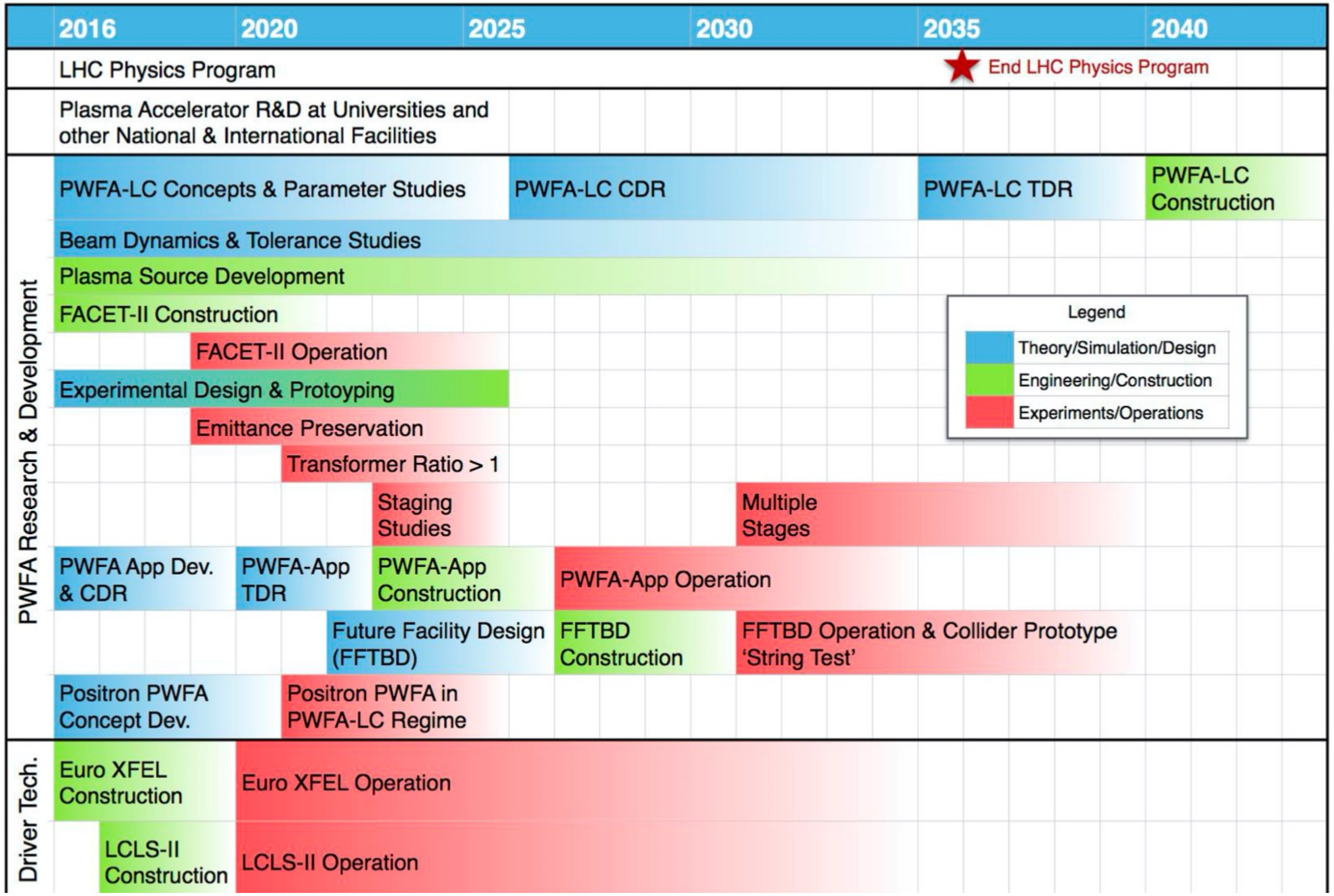
	Components				Performance Parameters				
Concept	**Accelerator Technology**	**Beam source**	**Interstage Coupling**	**Beam Delivery**	**Effective Gradient**	**Energy**	**Luminosity**	**Efficiency**	**Power (no recovery)**
ILC	SC RF	Damp. Ring	N/A	ILC BDS	31.5 MV/m	0.5 TeV	2.7E34		240 MW
AALC	Plasma or Str.	Damping	Trad. mag.	Trad. BDS	1 GeV/m	1 TeV	1E34	15%	70-100 MW
AALC	Plasma or Str.	Damping	Mag. or Plasma	Trad. BDS	1 or 10 GeV/m	3 TeV	3E34	15%	185-315 MW
AALC	Plasma or Str.	Plas. cath.@nm	Mag. or Plasma	Trad. BDS	1 or 10 GeV/m	3 TeV	1E35	15%	200-315 MW
AALC	Plasma or Str.	Plas. cath.@nm	Plas. lens	Trad. BDS	10 GeV/m	15 TeV	1E35	15%	900-1100 MW
AALC	Plasma or Str.	Plas. cath.@nm	Plas. lens	Plas. lens	10 GeV/m	15 TeV	5E35	15%	900-1100 MW

EF: Particle physics signature analysis needed to guide development, alternatives

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



Beam driven roadmap (example: similar for laser plasma & structures)



Parallel development of three methods mitigates risk

- Laser-plasma wakefield (LWFA)
- Beam plasma wakefield (PWFA)
- Structure wakefield (SWFA)

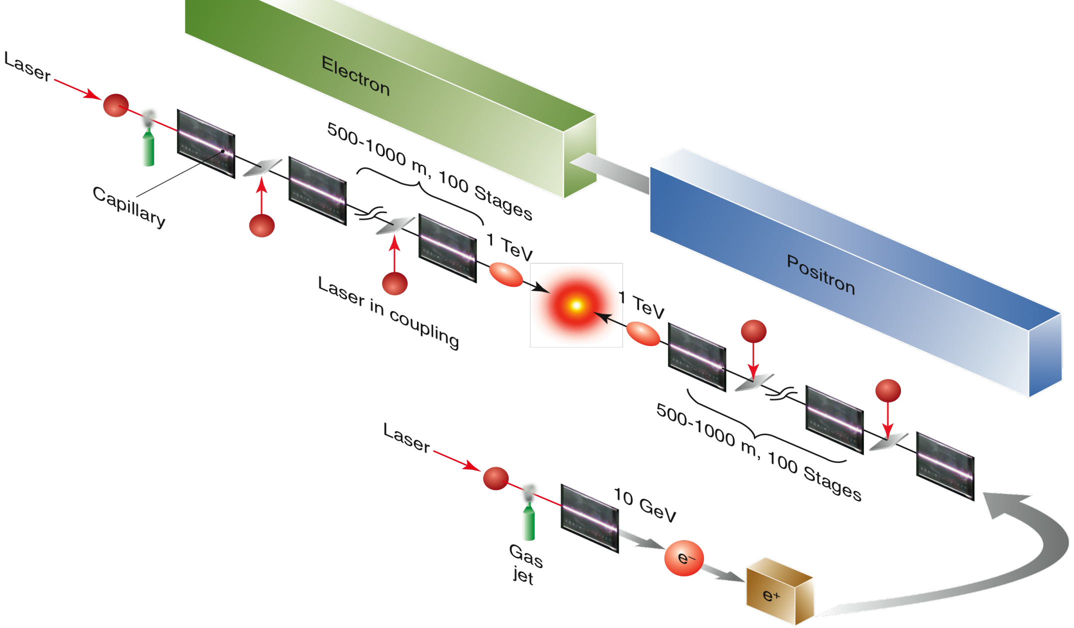
Similar collider parameters

New ideas offer potential for even greater future performance: laser structures, nanoplasma, flying focus…

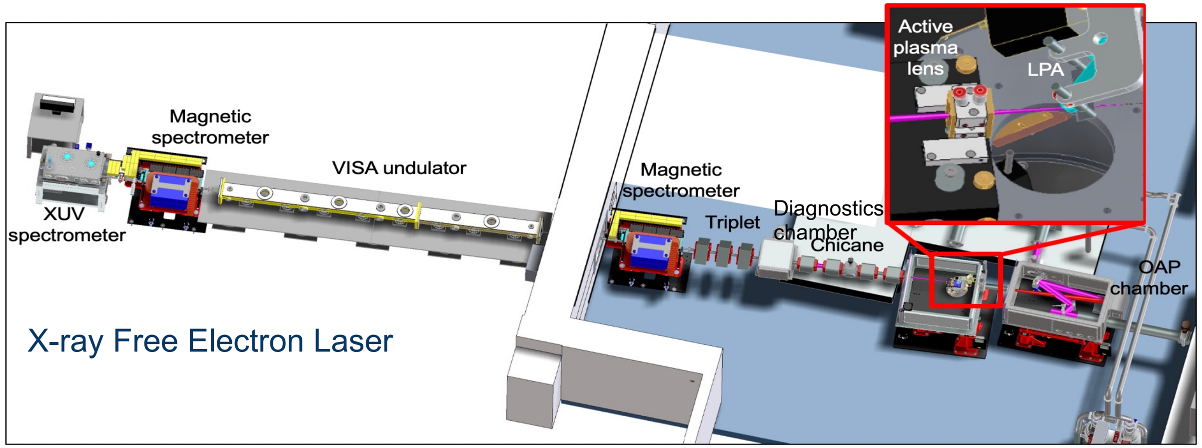
Technologies in R&D stage to date: now ready for integrated design study

Laser-driven plasma-based accelerators (LWFA)
2016 U.S. National Advanced Accelerator Development Strategy

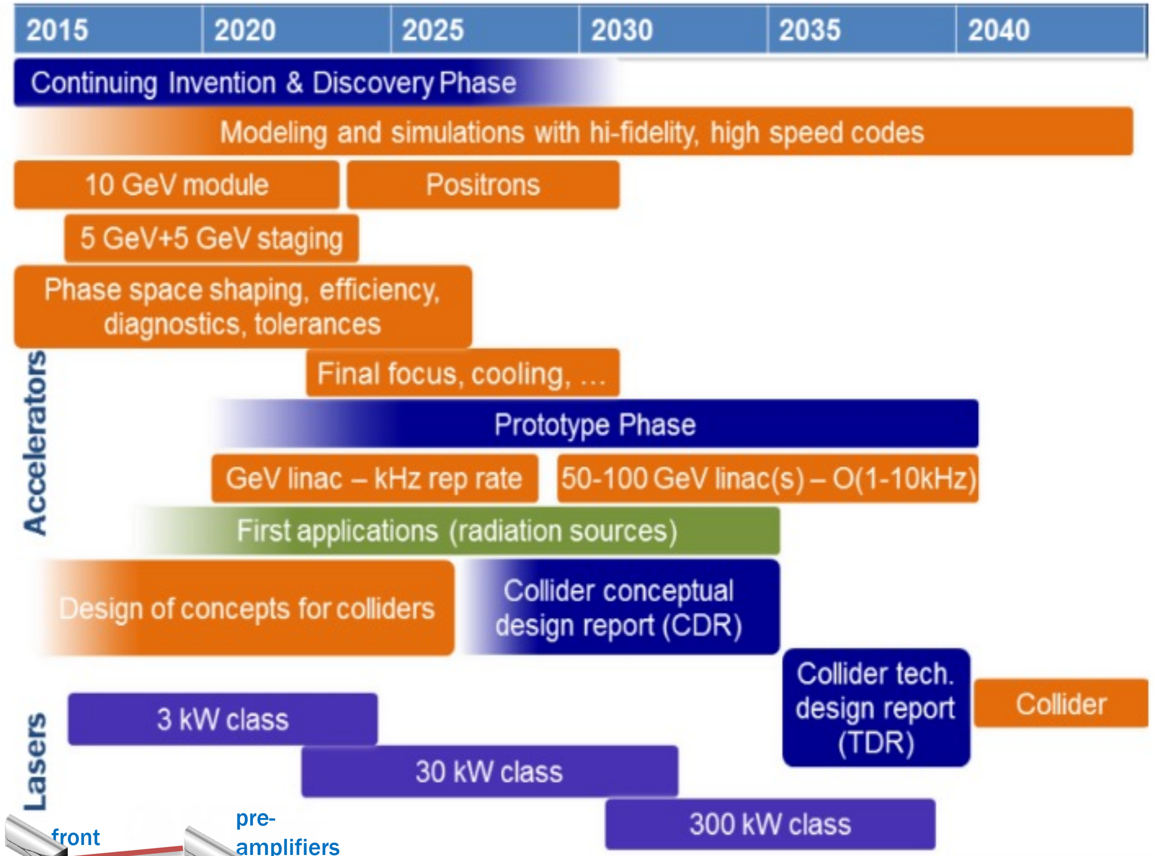
Long-term vision: high energy collider

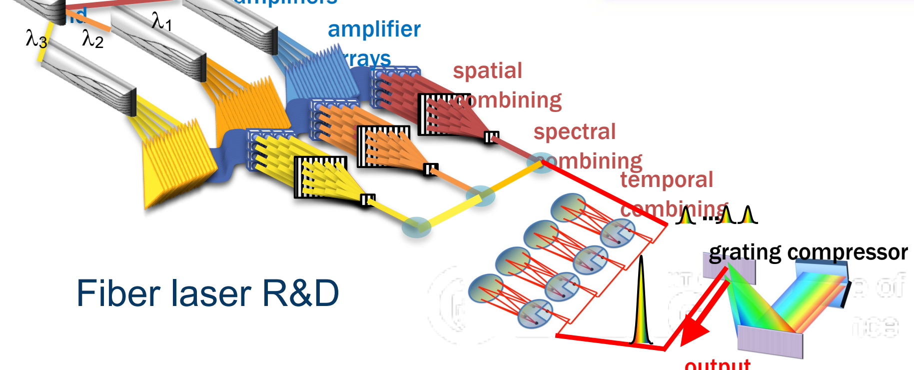


Near-term applications: compact light sources



X-ray Free Electron Laser

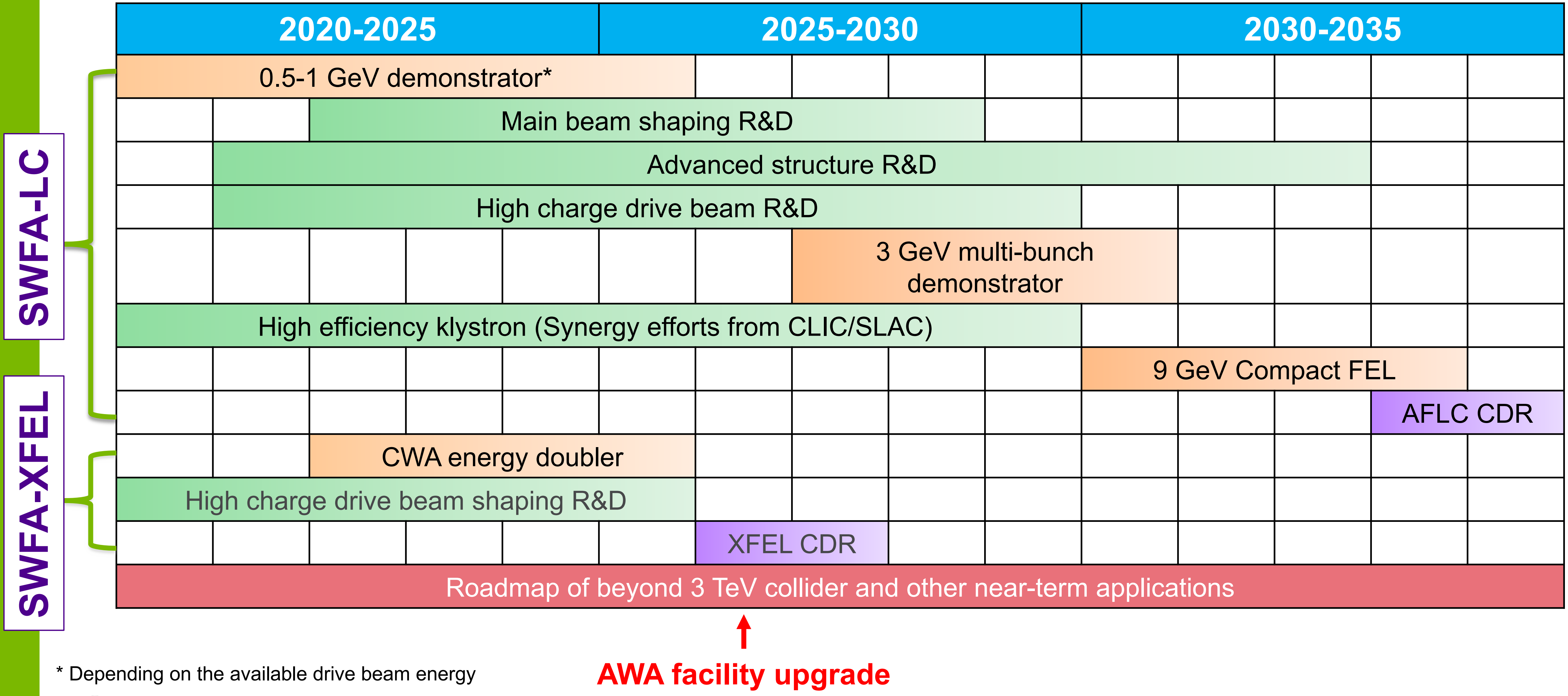




Fiber laser R&D

SWFA 15-YEAR ROADMAP

- Integral Demonstrator
- Key component
- Milestone report

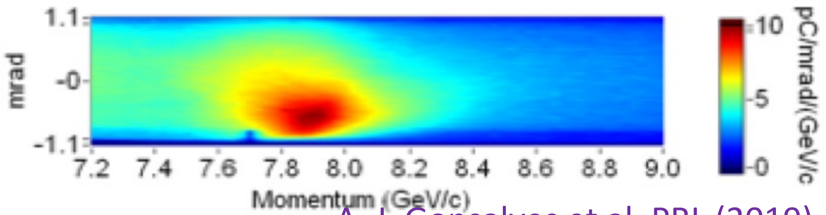


* Depending on the available drive beam energy

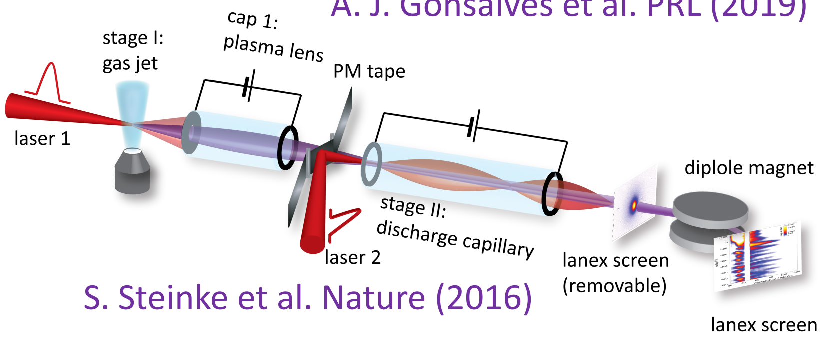
Rapid experimental progress since last Snowmass

- 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)
- Proof-of-principle staging of LWFAs (~100 MeV energy gain) using plasma-based stage coupling; multi-GeV soon
- Optimized beam loading in PWFA enables uniform, high-efficiency acceleration
- Demonstration >1 GeV/m gradients SWFA dielectric structures
- X-ray FEL at 27nm by LWFA (Shanghai 2021)
  Demonstrate beam quality
- New laser technology (fibers, Thulium) promise high average power at high efficiency

Also: positron PWFA, hollow channels for low emittance growth, laser-triggered injection for 0.1 micron emittance with path to nm-class…

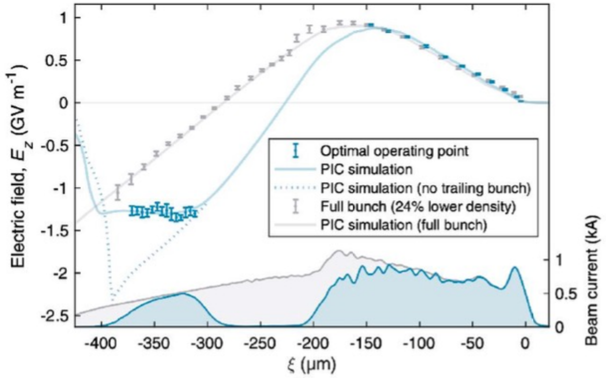


A. J. Gonsalves et al. PRL (2019)



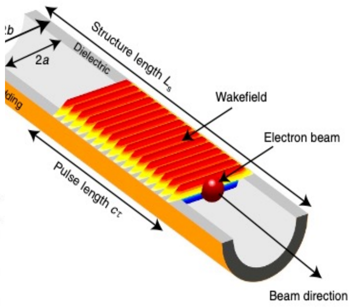
S. Steinke et al. Nature (2016)

42% transfer efficiency with 0.2% energy spread



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

GeV/m structure

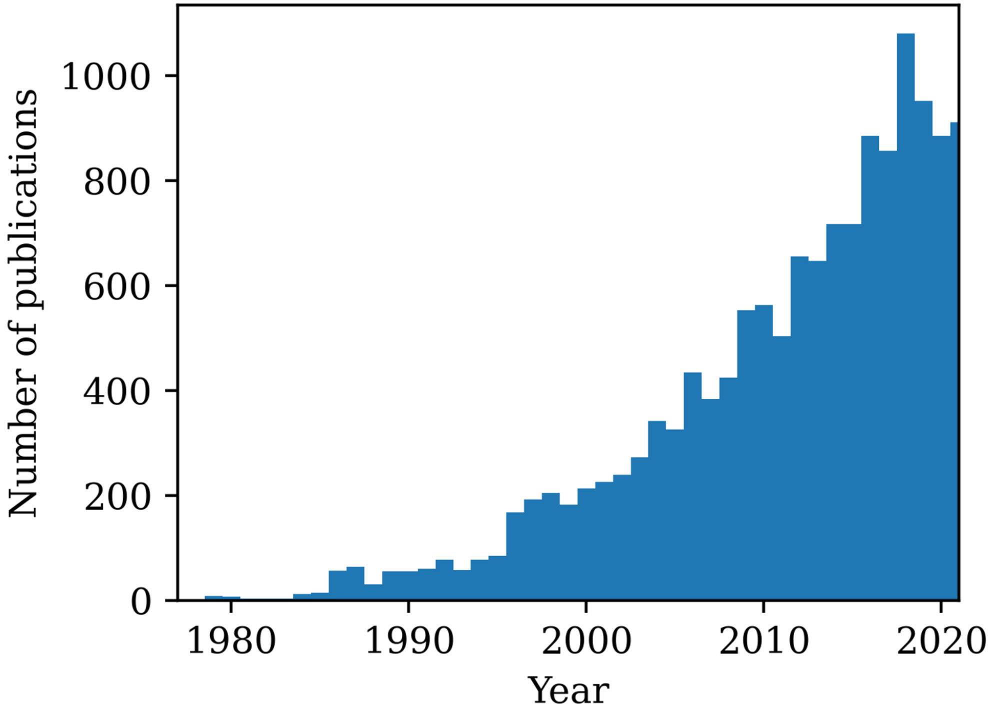


B. O'Shea et al. Nature Comm. (2016

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

Worldwide research on ANA is vigorous and rapidly evolving

- Example: Journal publications on laser-plasma wakefield accelerators
- > 1000 papers/year!
- Intense international competition: potential loss of US leadership



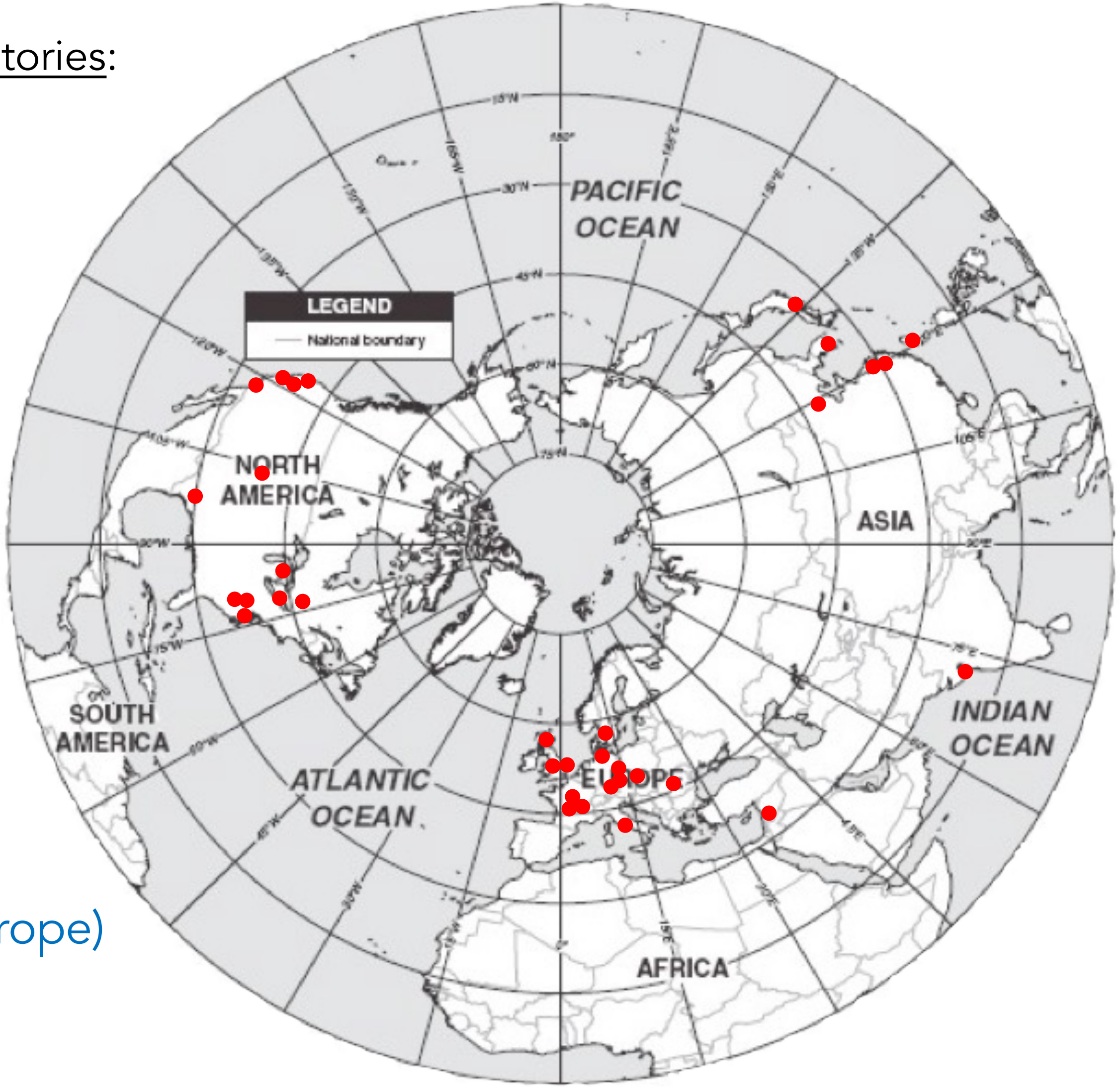
Google Scholar Search
Journal publications
containing the phases:
'Laser' and
'Plasma' and
'Wakefield' and
'Acceler*'.
(citations excluded)

- Laser R&D is also vigorous and rapidly evolving
- 2018 Nobel Prize in physics for chirped pulse amplification lasers (Strickland and Mourou)

LWFA R&D facilities world-wide

US LWFA R&D Laboratories:

- LBNL – BELLA
- LLNL – JLF
- BNL – ATF
- SLAC – MEC
- U. Texas
- U. Michigan
- LLE (Rochester)
- U. Nebraska
- NRL
- UCLA
- U. Maryland



Extreme Light Infrastructure (Europe) > 1 B euro

- Compactness of laser systems has led to proliferation of LWFA R&D in laboratories and universities world-wide

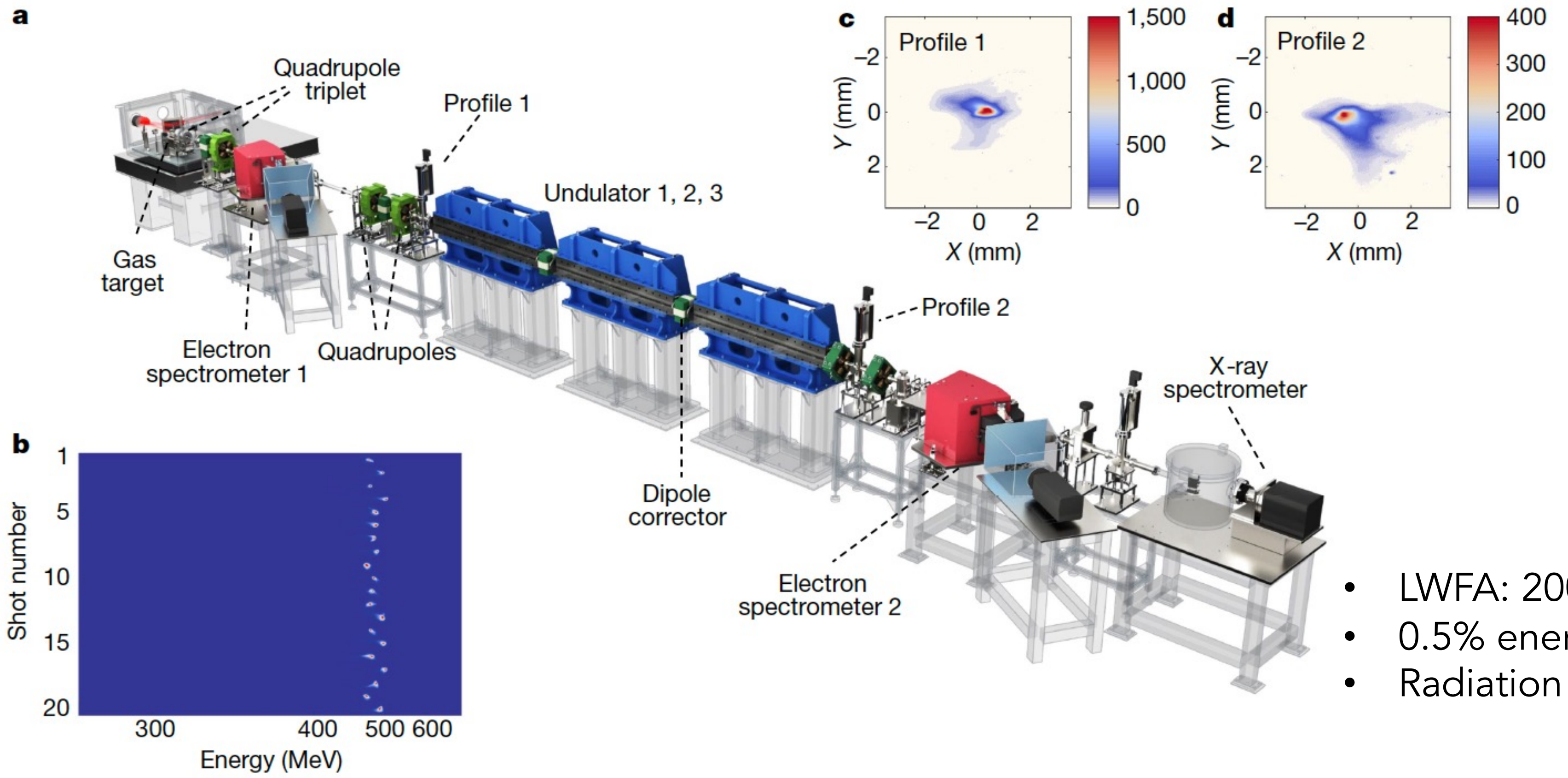
International LWFA R&D Laboratories:

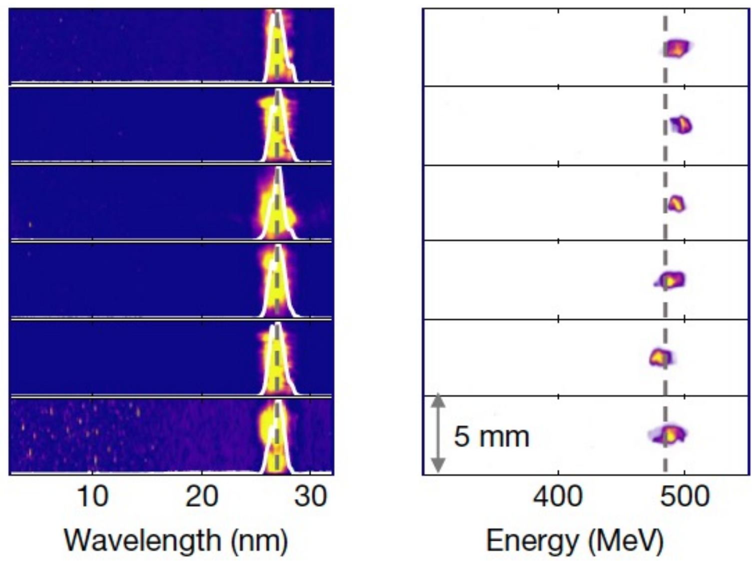
- ELI-Beamlines (Czech)
- ELI-NP (Romania)
- U. Lund (Sweden)
- HZDR (Germany)
- DESY (Germany)
- LMU (Germany)
- Jena (Germany)
- RAL (UK)
- SCAPA (UK)
- U. Oxford (UK)
- LOA (France)
- Apollon (France)
- LULI (France)
- INFN (Italy)
- CoReLS (Korea)
- KPSI (Japan)
- Tsinghua U. (China)
- SIOM (China)
- SJTU (China)
- TIFR (India)
- IAMS (Taiwan)
- ALLS (Canada)
- Weizmann Inst. (Israel)

Plasma accelerator driven photon sources

- Plasma-accelerator based photon sources naturally are on the R&D path to a collider
  - First lasing of FEL using laser plasma wakefield accelerator (LWFA) at 27 nm at SIOM (Shanghai, China)

Wentao Wang, Ke Feng, et al., "Free-electron lasing at 27 nanometres based on a laser wakefield accelerator" **Nature** 595, 516 (2021)

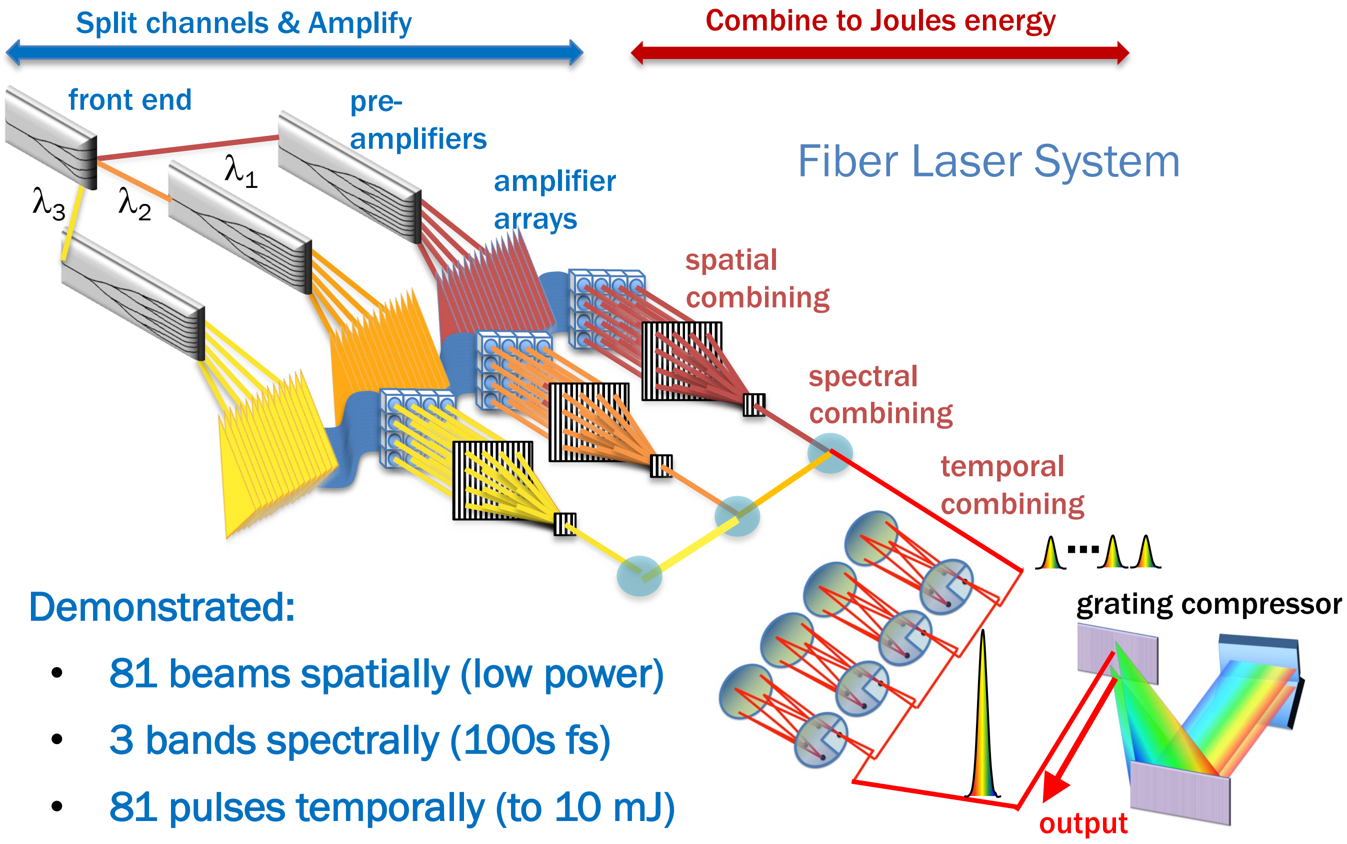




- LWFA: 200 TW used to generate 490 MeV e-beams
- 0.5% energy spread, ~0.5 um emittance
- Radiation up to 150 nJ / pulse (100-fold gain)

- First lasing of FEL (830nm) using beam-driven plasma accelerator (PWFA) reported at SPARC_LAB (INFN, Italy)

New Technology: Route to Very Efficient, High Average Power Ultrafast Lasers



Demonstrated:

- 81 beams spatially (low power)
- 3 bands spectrally (100s fs)
- 81 pulses temporally (to 10 mJ)

Path to Joules at 30-100fs

- Efficiency circa 30%
- Rates of 10-100 kHz

Approach: Coherent addition of fiber lasers

- Most efficient, potential monolithic integration

Challenge: Fibers < mJ each, typically > 100fs

Solution: Combine pulses in space, in color, & in time

- Spatially combine 100's fibers for Joules, 100's kW (in 3 bands and 100 pulses)
- Spectrally combine 3 bands for 30 fs
- Temporally combine 100 pulses to a single pulse

Alternatives: solid-state lasers based on Thulium, Yb

DOE Stewardship → Moore Foundation → kBELLA → Collider drivers

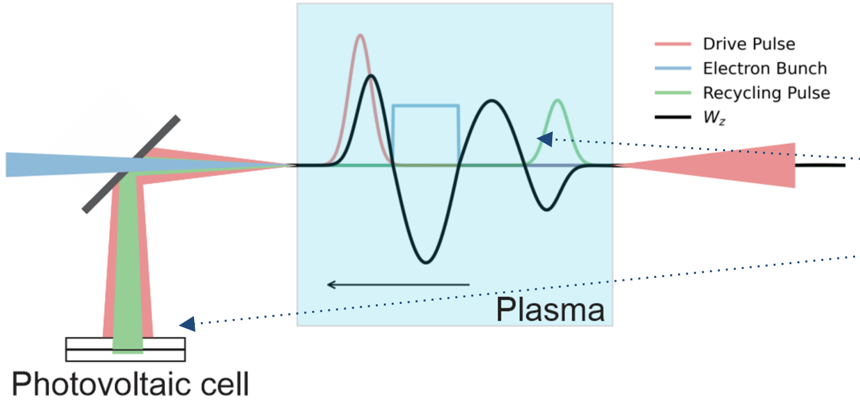
R&D → Facility

	DOE Stewardship	Moore Foundation	kBELLA	Collider drivers
Estimated completion date	2023	2025	2030	2036
Energy, Rep-rate	0.1 J, 1 kHz	0.2 J, multi kHz	1 J, multi kHz	multi J, tens kHz
Pulse duration	100 fs	30-50 fs	30-40 fs	30-100 fs

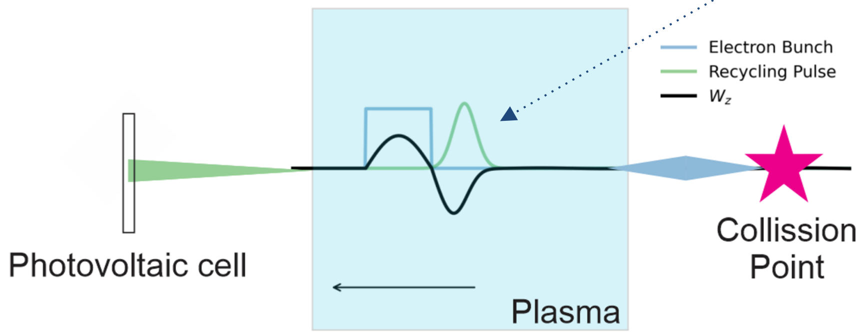
Energy Recycling for Plasma-Based Colliders

Concept: Use of a recycling pulse to sweep up energy remaining in wakefields, then return laser energy to the grid using wavelength targeted high-efficiency photovoltaic cells.

1) Energy-Recycling from Wakefields and Undepleted Drive Pulses (Implemented for each Acceleration Stage)



2) Energy-Recycling from Beams (After the Interaction Point)



Recycle energy from:
1) wakefields,
2) undepleted drivers,
3) beams after the IP.

⇒ Reuse recycling pulses or recycle their energy by high-efficiency, wavelength targeted photovoltaic cells (η_{PVC} ~ 0.7-0.9).

Potential impact:

- Decrease power consumption of a linear plasma based collider by 40-80%.
- Decrease environmental impact by reducing energy deposited on beam dump.
- Reduce plasma cooling requirements and potentially increase luminosity.

Marlene Turner et al.

Assessment of limits indicates potential for 15 TeV-class

- ANA community has accessed potential limits of high-gradient linac technology
  - Shaped bunches for *high efficiency acceleration* without energy spread growth
  - Ion motion induced by dense beams can *mitigate transverse hosing instability*
  - *Scattering* in plasma mitigated by strong plasma focusing
  - *Positrons* can be accelerated in plasma columns
  - 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 ANA
  - Beamstrahlung limits bunch charge and luminosity requirements increase required power:
  - Short beams and low emittance reduce power requirements
  - High gradients could enable practical energy recovery

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

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

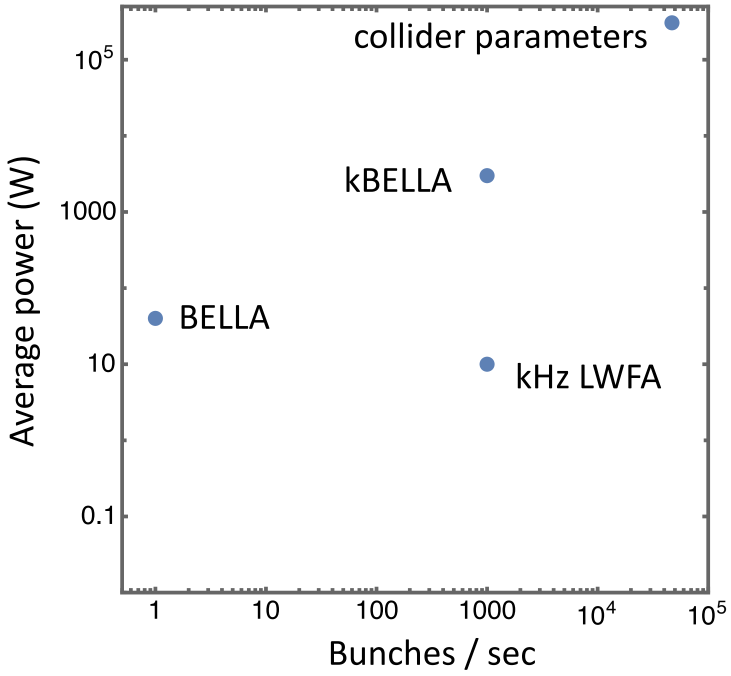
Next Steps: ANA facility upgrades will advance technology and test key remaining parameters

- Rapid investment in Europe, Asia, incl. EuPRAXIA ($600M-class)
  - US R&D, facility base creates leadership opportunities

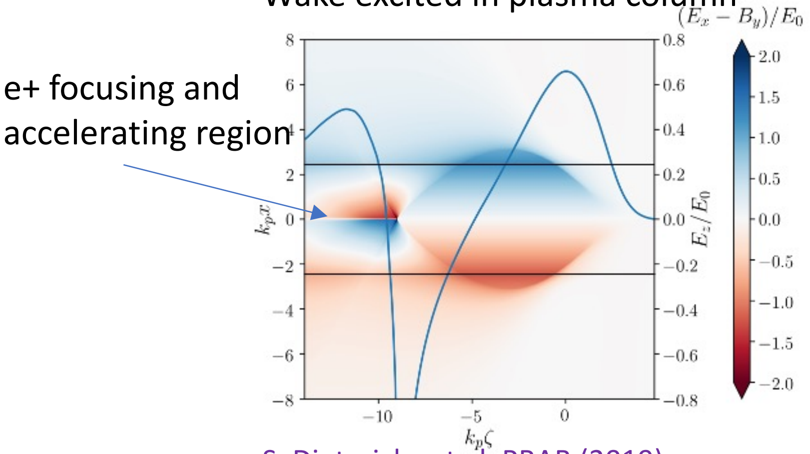
- High-average power and high repetition rate plasma accelerators:
  - *Technical challenges*: targetry at repetition rate, heat deposition and management (~kW/cm), structure durability
  - *kBELLA project*: kHz, J-class laser. Technology available; precision via active feedback, applications on collider roadmap

- 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)

- Near term applications will establish technology, benefit colliders
  - Compton MeV photon sources, FELs, nQED, injectors… societal benefit and increased return on investment for HEP



Wake excited in plasma column



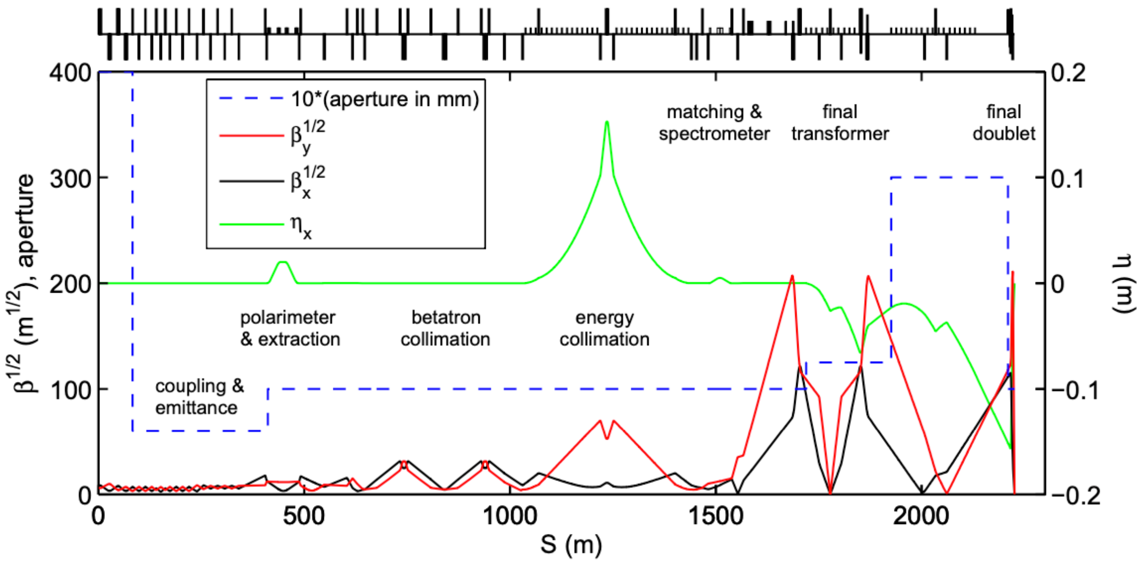
S. Dieterichs et al. PRAB (2019)

Integrated Design Study required: linacs + auxiliary systems

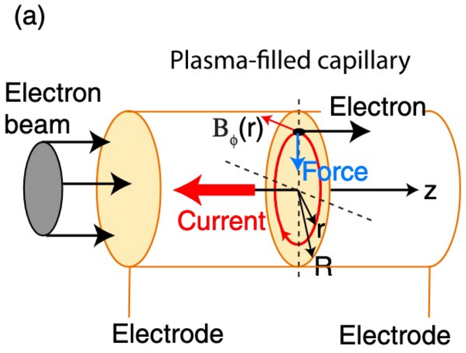
Example: BDS system

- A traditional BDS system contains diagnostic sections and collimation sections in addition to the Final Focus and Machine-Detector Interface.
  - Can we develop novel diagnostics (e.g. betatron radiation) to characterize the beam emittance?
  - Can we develop novel collimation schemes?
- The Final Focus uses the local chromatic correction in the final doublet.
  - Can we employ novel chromatic correction techniques with shaped plasma lenses?
  - Can we reduce the beam spot using strong focusing from plasma lenses?
- Bunch format: default evenly spaced 10-100kHz class (10-100μs), other formats possible

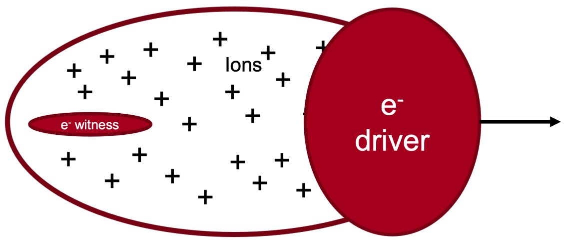
ILC BDS



Active Plasma Lens



Passive Plasma Lens



Intermediate Term: ANA Collider Facility 20-100 GeV

Whitepaper submitted to Snowmass21: Advanced accelerator linear collider demonstration facility at intermediate energy

C. Benedetti, S. S. Bulanov, E. Esarey, C. G. R. Geddes A. J. Gonsalves, P. M. Jacobs, S. Knapen, B. Nachman, K. Nakamura, S. Pagan Griso, C. B. Schroeder, D. Terzani, J. van Tilborg, M. Turner, W.-M. Yao, R. Bernstein, V. Shiltsev, S. J. Gessner, M. J. Hogan, T. Nelson, C. Jing, I. Low, X. Lu, R. Yoshida, C. Lee, P. Meade, N. Vafaei-Najafabadi, P. Muggli, P. Musumeci, M. Palmer, E. Prebys, L. Visinelli, C. A. Aidala, A. G. R. Thomas

- Intermediate facility: 20-100 GeV ANA-based lepton collider

- Technology demonstrator
  - test beam facility for accelerator and detector studies

- Physics studies
  - charged particle interactions with extreme fields (SF-QED, beam delivery and IP studies)
  - muon production and acceleration
  - precision Quantum Chromodynamics
  - Beyond the Standard Model physics: milli-charged particles; inelastic DM; low mass resonances; axion-like particles

- Need input from community for physics case

European Endorsements

2020 Update of the European Strategy for Particle Physics

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.

2022 European Laboratory Directors Group Report

The field of high-gradient plasma and laser accelerators offers a prospect of facilities with significantly reduced size that may be an alternative path to TeV scale e+e- colliders.

The expert panel has defined a long term R&D roadmap towards a compact collider with attractive intermediate experiments and studies.

The panel recommends strongly that the particle physics community supports this work with increased resources in order to develop the long term future and sustainability of this field.

International community working toward addressing collider R&D challenges

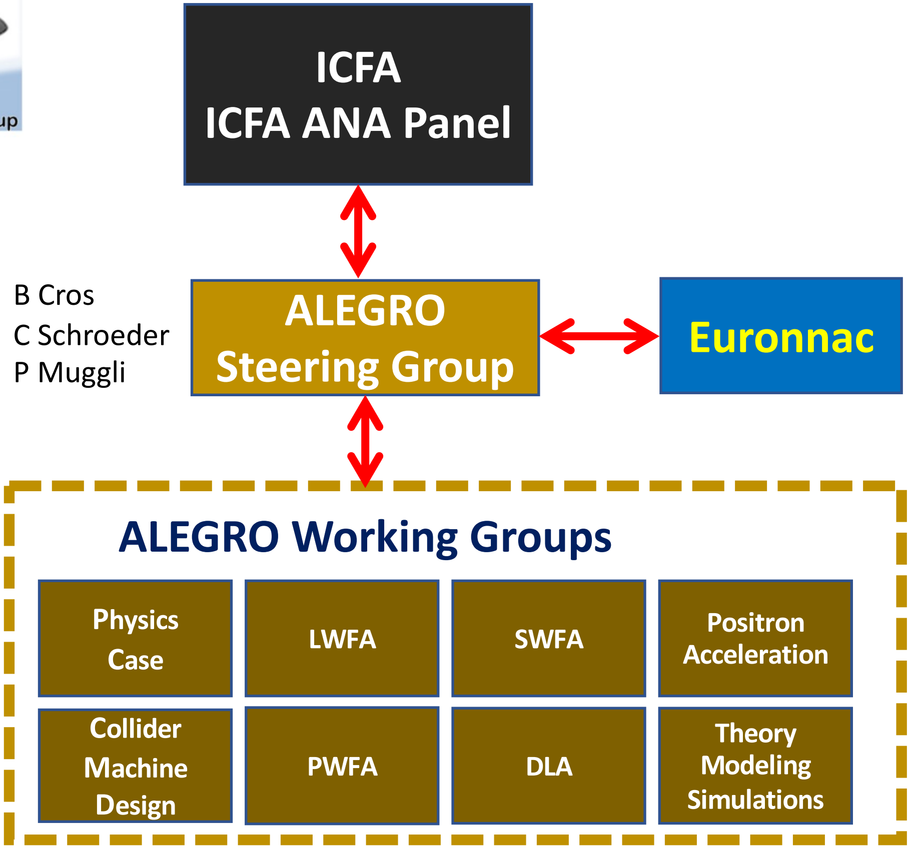
Advanced LinEar collider study GROup

http://www.lpgp.u-psud.fr/icfaana/alegro

Advanced LinEar collider study GROup

- Foster Advanced Linear Collider activities based on Advanced and Novel Acceleration (ANA) concepts
- Framework to amplify international coordination, broaden the community, involving accelerator labs/institutes
- Identify topics of ANAs requiring intensive R&D and facilities needed

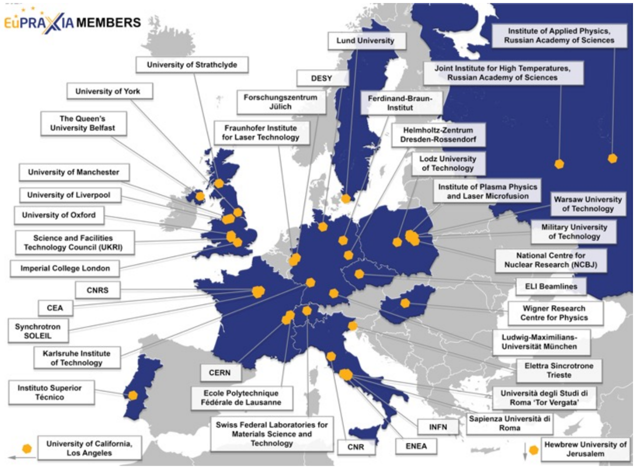
- Worldwide
- R&D for all aspects of collider design



- Input document for the European Strategy — arXiv:1901.08436
- Global Scientific Roadmap — arXiv:1901.10370
- Development of an Advanced Linear Collider (ALIC) at the energy frontier
- Contribution to the US strategy

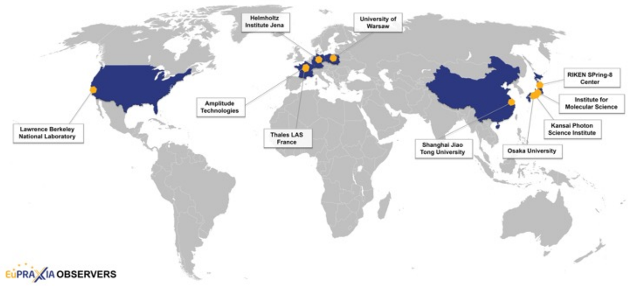
European Plasma Research Accelerator with eXcellence In Applications

Distributed RI Involving 50 Institutes from 15 Countries



LNF-INFN
Frascati, Rome, Italy

Construction Site & Head-quarter



Ideas & Talents
Collaboration
Open Innovation
Opportunity

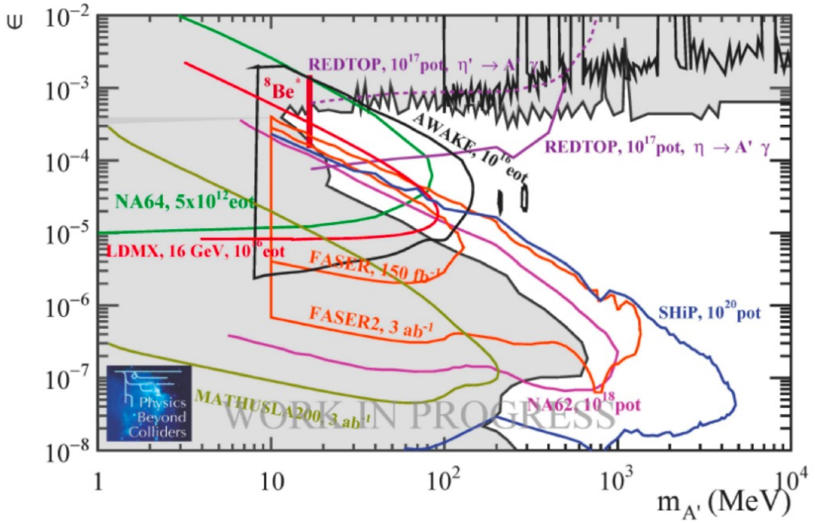
Start of user operation
beam-driven plasma accelerator in Frascati: **2028**

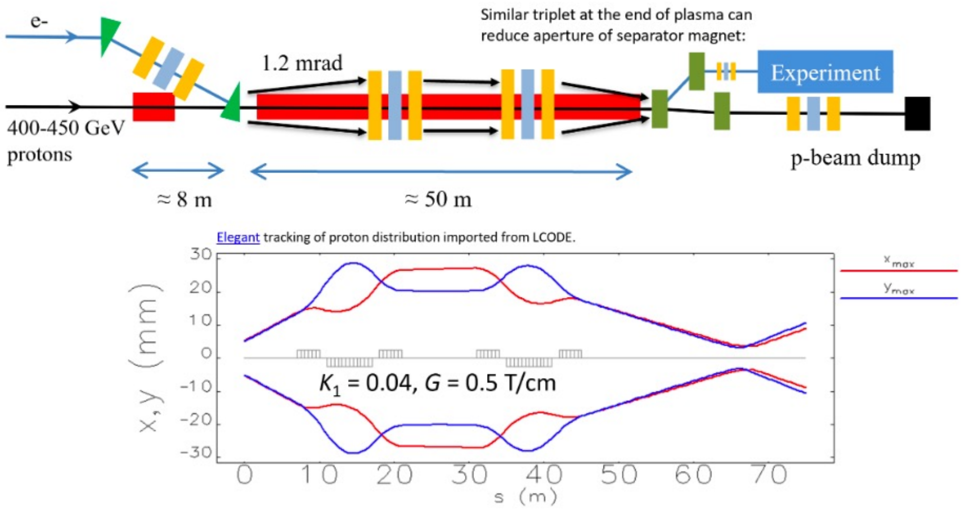
2nd construction site in Europe for a laser-driven plasma accelerator facility to be decided in two years

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

AWAKE++ Beam Dump Experiment

AWAKE at CERN uses a proton beam to drive the plasma wakefield and accelerate electrons to energies greater than 50 GeV. They have identified part of the dark photon parameter space as a target application.





[AWAKE++: the AWAKE Acceleration Scheme for New Particle Physics Experiments at CERN]

Plasma and Advanced Structure Colliders: Summary

- ANA: potential for multi-TeV collider
  - 1-10 GV/m: compact linacs
  - Ultrashort bunches: reduce power
  - Gamma-gamma, polarized e+e-
- Vigorous research, rapid progress
  - >1000 pubs/yr
- Strong European endorsement
  - EuPRAXIA
- Next Steps: Upgrade existing facilities
  - Remain productive and competitive
  - Ensure progress on R&D roadmap
- Need for integrated design study
  - Include auxiliary systems
- Need design for intermediate energy facility
  - Build physics case 20-100 GeV
- Intermediate applications
  - Light sources, compact accelerators
- Need input from HEP community
  - Physics case
  - Guide design of future facilities

Revision of ANA Roadmaps: in progress