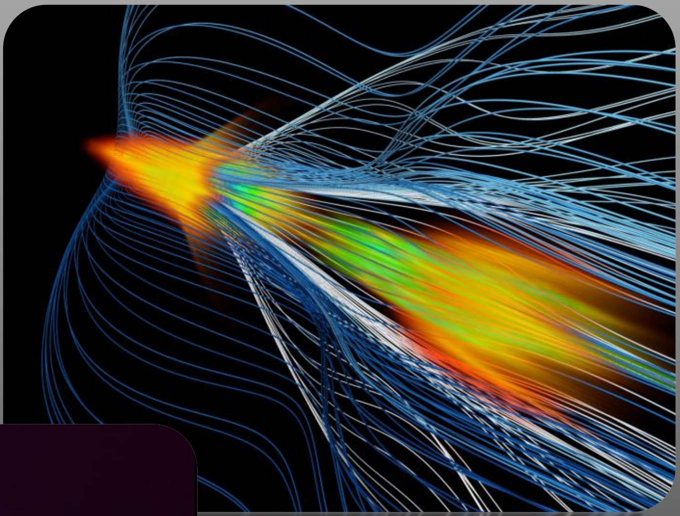
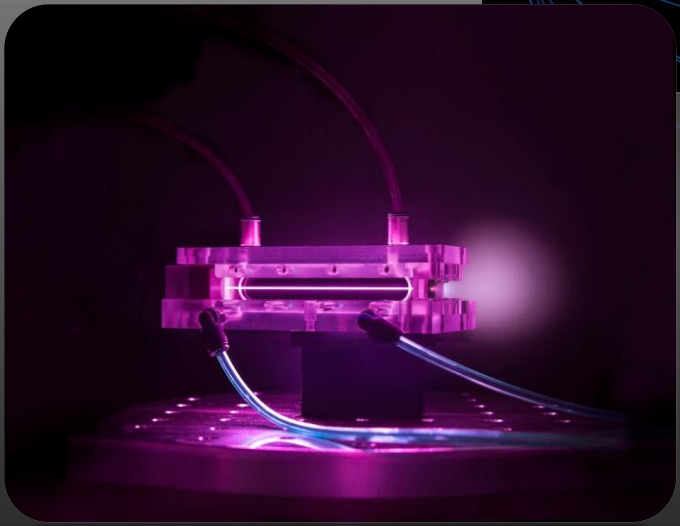
U.S. DEPARTMENT OF ENERGY | Office of Science

Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop

February 2–3, 2016





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Introduction

Over a full two day period, February 2–3, 2016, the Office of High Energy Physics convened a workshop in Gaithersburg, MD to seek community input on development of an Advanced Accelerator Concepts (AAC) research roadmap. The workshop was in response to a recommendation by the HEPAP Accelerator R&D Subpanel [1] [2] to "*convene the university and laboratory proponents of advanced acceleration concepts to develop R&D roadmaps with a series of milestones and common down selection criteria towards the goal for constructing a multi-TeV e^+e^- collider*" (the charge to the workshop can be found in Appendix A). During the workshop, proponents of laser-driven plasma wakefield acceleration (LWFA), particle-beam-driven plasma wakefield acceleration (PWFA), and dielectric wakefield acceleration (DWFA), along with a limited number of invited university and laboratory experts, presented and critically discussed individual concept roadmaps. The roadmap workshop was preceded by several preparatory workshops.

The first day of the workshop featured presentation of three initial individual roadmaps with ample time for discussion. The individual roadmaps covered a time period extending until roughly 2040, with the end date assumed to be roughly appropriate for initial operation of a multi-TeV e^+e^- collider. The second day of the workshop comprised talks on synergies between the roadmaps and with global efforts, potential early applications, diagnostics needs, simulation needs, and beam issues and challenges related to a collider. During the last half of the day the roadmaps were revisited but with emphasis on the next five to ten years (as specifically requested in the charge) and on common challenges. The workshop concluded with critical and unanimous endorsement of the individual roadmaps and an extended discussion on the characteristics of the common challenges. (For the agenda and list of participants see Appendix B.)

Overall Timescale and Common Challenges

The primary long-term goal of a multi-TeV collider provides an overarching timescale for the AAC roadmap as embodied by completion of a technical design report (TDR) sometime in the 2035–2040 interval. Completion of a TDR for a potential early application in the 2025–2030 interval serves as an intermediate goal. Likely early applications might be an X-ray Free Electron Laser (XFEL) and a gamma-ray source. These two goals and their associated time scales provide the broadest context for the AAC roadmap.

The next ten years of AAC research should focus on addressing common challenges identified during the workshop:

1. Higher energy staging of electron acceleration with independent drive beams, equal energy, and 90% beam capture;
2. Understanding mechanisms for emittance growth and developing methods for achieving emittances compatible with colliders;
3. Completion of a single electron acceleration stage at higher energy;
4. Demonstration and understanding of positron acceleration; and
5. Continuous, joint development of a comprehensive and realistic operational parameter set for a multi-TeV collider, to guide operating specifications for AAC.

The phrase "higher energy" in the first and third common challenges encompasses the different capabilities of the concepts and facilities and is taken to be in the multi-GeV range for LWFA and PWFA and in the multiple-100 MeV range for DWFA.

The following concept roadmaps for LWFA, PWFA, and DWFA have been developed in the framework of the overarching time scale and in response to the common challenges. An additional roadmap is included for laser development in support of LWFA, stewardship of laser technology should not be overlooked. Of course, significant differences exist for the concepts due to differences in their technical nature and readiness. In particular, certain aspects of the DWFA effort could be incorporated in current collider designs. The report concludes with comments on possible synergies between the concepts and support needed for simulation development.

LWFA and Laser Technology Roadmaps, Including Ten Year Detailed R&D Roadmap

The research program toward completion of a technical design report (TDR) for a multi-TeV e^+e^- linear collider based on LWFA technology, anticipated in the 2035-2040 time frame in order to meet needs for machines following the Large Hadron Collider, is presented in Fig. 1. Construction would begin thereafter.

In preparation for development of a conceptual design, R&D over the next ten years would continue the ongoing invention and discovery phase, where the main goals would be understanding of the key physics concepts and innovation of LWFA collider concepts. The primary challenges were enumerated in the introductory section of this document. This phase would include experiments demonstrating significant progress toward the collider goal (see Fig. 2). To identify and solve outstanding physics and technology issues several key experiments are required.

Presently LWFA can accelerate tens of pC of charge to several GeV in a single stage [3]. The ten-year R&D goal is to accelerate 100 pC of charge to 10 GeV in a single LWFA stage. Accomplishing this requires development of techniques for matched guiding of the laser pulse in the plasma. Other R&D would be focused on improvements in stability, reproducibility, and tunablity, which will enable near-term applications.

With the completion of a 10 GeV electron LWFA stage, the 10 GeV beam may be employed for electron-positron pair creation and subsequent positron beam capture and LWFA. Development of an LWFA-based positron source would enable compact experiments on LWFA and focusing of positron beams.

Critical to the collider application is demonstration of multi-GeV LWFA staging with independent, equal energy, drive beams. Following the successful demonstration of LWFA staging at the 100-MeV-energy level [4], a multi-GeV (e.g., 5 GeV and 5 GeV) staging experiment is required. The goal of this experiment is to demonstrate high beam capture efficiency (>90%), while maintaining a large average/geometric accelerating gradient (>5 GV/m) and preserving the beam emittance between LWFA stages. This experiment will allow study and understanding of emittance growth mechanisms, as well as testing of growth mitigation techniques.

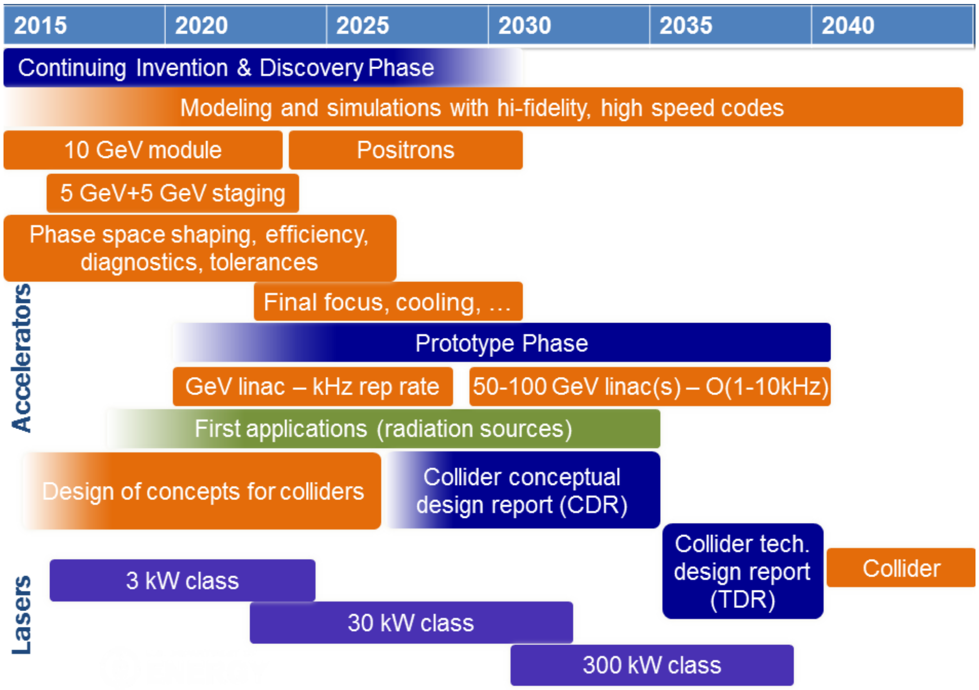
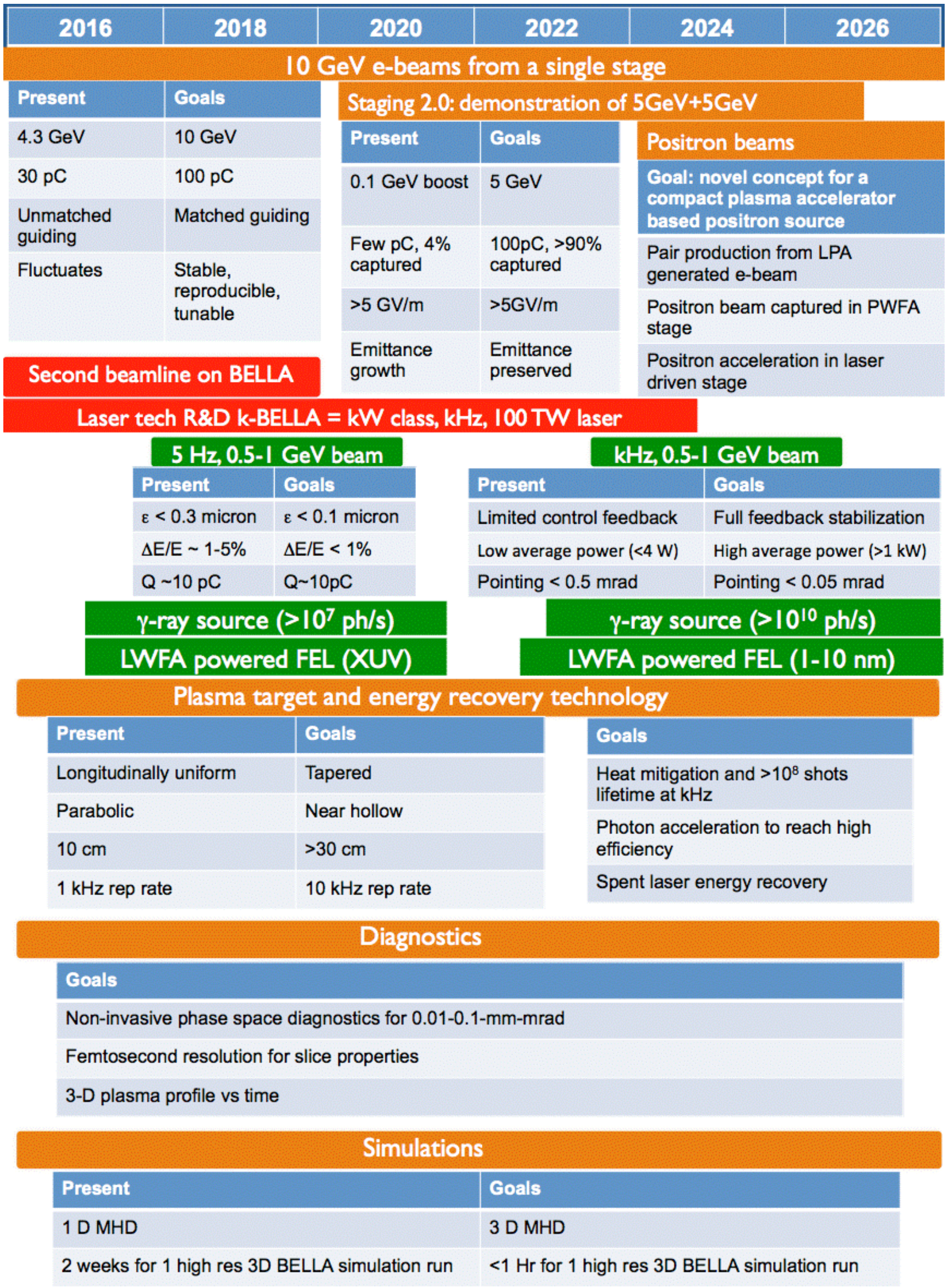


Figure 1: Roadmap for the development of a LWFA based collider, which lays out phases for invention and discovery (during the next decade), the emergence of first applications, and prototype demonstrators. A conceptual design study could occur in the 2025-2035 time frame, followed by a five year technical design study, culminating with start of construction around 2040.

Plasma target development is required to enable the key experiments. Shaping and precise control of plasma target profiles is required for the collider application. In particular, development of longitudinally-tapered and near-hollow plasma channels, extending tens of centimeters, requires R&D.

Of crucial importance will be a deep understanding of how to optimize the efficiency from laser beam to particle beam, and what the limitations are towards the ultimate performance that would make this technology operate at levels superior to present day technology for accelerators. Novel methods for extracting energy from plasma wakes via particle bunch shape (or current pulse) tailoring must be developed, techniques to reduce the remaining wake energy (and hence also reducing the power loading on the structures) by “soaking up” the wake energy using additional laser pulses, and direct conversion of power in intense lasers exiting the plasma structures using photo-voltaic optical to electric conversion systems which is unique to using lasers as drivers. Methods for bunch shape tailoring and wake energy extraction would also benefit the beam driven plasma systems.

Contemporaneously to the demonstration of key experiments, novel diagnostics for LWFA beams and plasma targets must be invented and high-fidelity and high-speed simulation tools must be developed. Modeling of plasma targets will require 3D magneto-hydrodynamic (MHD) codes to be developed, with the proper low-temperature physics and chemistry included. The development of the MHD codes will benefit from collaborations with LLNL and SNL, leveraging NNSA investments. Capabilities for rapid modeling of multi-GeV-LWFA stages (laser and beam plasma interaction) are required for parameter exploration and start-to-end modeling of LWFA-based colliders. This requires a sustained community effort on development of open source code



2016	2018	2020	2022	2024	2026

10 GeV e-beams from a single stage

Present	Goals
4.3 GeV	10 GeV
30 pC	100 pC
Unmatched guiding	Matched guiding
Fluctuates	Stable, reproducible, tunable

Staging 2.0: demonstration of 5GeV+5GeV

Present	Goals
0.1 GeV boost	5 GeV
Few pC, 4% captured	100pC, >90% captured
>5 GV/m	>5GV/m
Emittance growth	Emittance preserved

Positron beams

Goal: novel concept for a compact plasma accelerator based positron source
Pair production from LPA generated e-beam
Positron beam captured in PWFA stage
Positron acceleration in laser driven stage

Second beamline on BELLA

Laser tech R&D k-BELLA = kW class, kHz, 100 TW laser

5 Hz, 0.5-1 GeV beam

Present	Goals
ε < 0.3 micron	ε < 0.1 micron
ΔE/E ~ 1-5%	ΔE/E < 1%
Q ~10 pC	Q~10pC

kHz, 0.5-1 GeV beam

Present	Goals
Limited control feedback	Full feedback stabilization
Low average power (<4 W)	High average power (>1 kW)
Pointing < 0.5 mrad	Pointing < 0.05 mrad

γ-ray source (>10^7 ph/s)

LWFA powered FEL (XUV)

γ-ray source (>10^{10} ph/s)

LWFA powered FEL (1-10 nm)

Plasma target and energy recovery technology

Present	Goals
Longitudinally uniform	Tapered
Parabolic	Near hollow
10 cm	>30 cm
1 kHz rep rate	10 kHz rep rate

Goals
Heat mitigation and >10^8 shots lifetime at kHz
Photon acceleration to reach high efficiency
Spent laser energy recovery

Diagnostics

Goals
Non-invasive phase space diagnostics for 0.01-0.1-mm-mrad
Femtosecond resolution for slice properties
3-D plasma profile vs time

Simulations

Present	Goals
1 D MHD	3 D MHD
2 weeks for 1 high res 3D BELLA simulation run	<1 Hr for 1 high res 3D BELLA simulation run

Figure 2: Ten-year LWFA roadmap and milestones. The orange boxes are activities, with present status and goals listed below. The red boxes denote facility investments that must occur to enable staging at multi-GeV energies (BELLA 2nd line) and a high average power demonstration facility (k-BELLA). The green boxes denote early applications that are enabled by the development of the LWFAs. Applications on the left and right hand side will be possible with today's lasers and with high repetition rate systems, respectively.

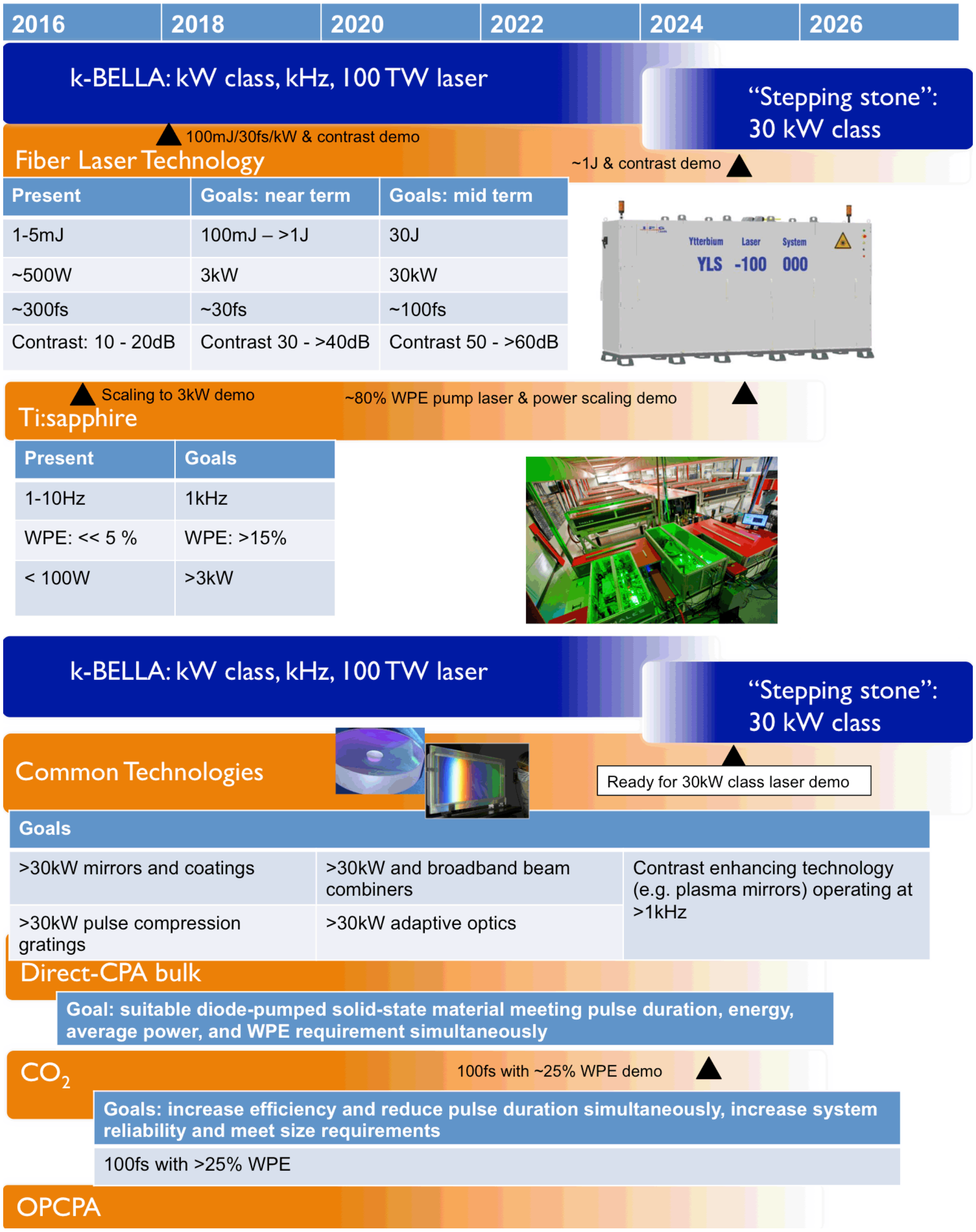
suites that integrate all the recent algorithmic advances (e.g. boosted frame, Maxwell solvers with azimuthal Fourier decomposition, spectral solvers, control of numerical Cherenkov instability, laser envelope solvers, adaptive mesh refinement) for the plasma-based accelerator modules with advanced beam dynamics modules for transport through conventional transport sections. Integration of all the above mentioned algorithmic advances, together with porting of the codes to massively parallel many core and GPU architectures, will enable speedups by orders of magnitude, from days-to-weeks at present for 3-D simulations of one multi-GeV stage, to minutes-to-hours on exascale-capable supercomputers.

These simulation tools must be validated with experimental measurements. Diagnostics are required to resolve femtosecond slice properties of the LWFA beam, and techniques for non-invasive beam phase space measurements (e.g., with resolution on the order of tens of nm normalized transverse emittance) are needed. Methods to measure the evolution of the 3D plasma profile are also required.

In addition innovative LWFA-collider concepts must be explored over the next ten years. For example, compact final focus methods with large momentum acceptance, rapid cooling methods for positron beams that are compatible with short (tens of microns) beams, and laser-plasma methods for generation of ultra-cold, polarized electron beams require investigation.

During the next ten years, the development of non-HEP applications of LWFA technology is a critical component of the collider R&D roadmap. Stable, reproducible, and tunable LWFA enables application of several-hundred-MeV to multi-GeV electron beams for light source applications. First applications considered over the next decade are a free-electron laser (FEL) powered by an LWFA, initially operating at XUV wavelengths, for ultra-fast science applications and a gamma-ray source, via Thomson scattering, producing MeV photons for nuclear detection. These light sources would initially operate at the few Hz repetition rate. Following successful demonstrations, and the development of kW-class laser systems, the FEL would be extended to the soft x-ray regime (few nm) at kHz rep rates, and the gamma-ray source would be capable of producing 10^{10} photons/second or more.

In parallel to the accelerator development, laser development is also required to realize a LWFA collider. In the next few years, R&D on kW average power laser systems will enable the fielding of a Joule, kHz laser system (“k-BELLA”) for LWFA R&D. At kHz repetition rates, studies of feedback and stabilization techniques are possible, enabling improved LWFA beam quality, as well as increased average beam power. A kW laser system allows testing of high-average power beam issues, such as heat mitigation and lifetime at kHz rep rates. To achieve the ~10 kHz rep-rates and high average powers needed for a collider requires further laser technology development. Approaches based on coherent combining of multiple fiber lasers, or on Ti:sapphire lasers, solid-state lasers, CO_2 lasers, and on OPCPA should be considered (see Fig. 3). Each of these approaches requires different R&D levels: some have a clear technology-development pathway towards LWFA drivers, others still need to address fundamental challenges. Laser technologies include development of high-power optics technology (mirrors, diffraction gratings, beam combiners) to withstand hundreds of kW of optical power, as well as techniques for achieving high pulse contrast at ~10 kHz. In addition, methods for improved efficiency should be investigated, including spent laser energy recovery and photon acceleration to remove energy remaining in the plasma wakefield.



Present	Goals: near term	Goals: mid term
1-5mJ	100mJ – >1J	30J
~500W	3kW	30kW
~300fs	~30fs	~100fs
Contrast: 10 - 20dB	Contrast 30 - >40dB	Contrast 50 - >60dB

Present	Goals
1-10Hz	1kHz
WPE: << 5 %	WPE: >15%
< 100W	>3kW

Goals		
>30kW mirrors and coatings	>30kW and broadband beam combiners	Contrast enhancing technology (e.g. plasma mirrors) operating at >1kHz
>30kW pulse compression gratings	>30kW adaptive optics	

Goal: suitable diode-pumped solid-state material meeting pulse duration, energy, average power, and WPE requirement simultaneously

Goals: increase efficiency and reduce pulse duration simultaneously, increase system reliability and meet size requirements

100fs with >25% WPE

Figure 3: Ten-year roadmap and milestones for laser technology development. In the next decade technology would be developed and implemented for a high average power demonstration facility (k-BELLA) at the few kW level, followed by scaling suitable technology to the tens of kW-level. The different technologies that are available today have different levels of maturity, but all require R&D albeit at different levels. R&D is also needed on common technologies such as mirror coatings, pulse compression and clean-up techniques (in both space and time).

PWFA Roadmap

The physics program at the Large Hadron Collider (LHC) will end around 2035. If plasma based accelerators are to meet the needs of international High Energy Physics Community, the R&D Roadmap must arrive at a design with a sufficient level of maturity to be considered as the next candidate machine. Consequently, PWFA R&D spanning the next 25 years is outlined in the long range roadmap presented in Fig. 4.

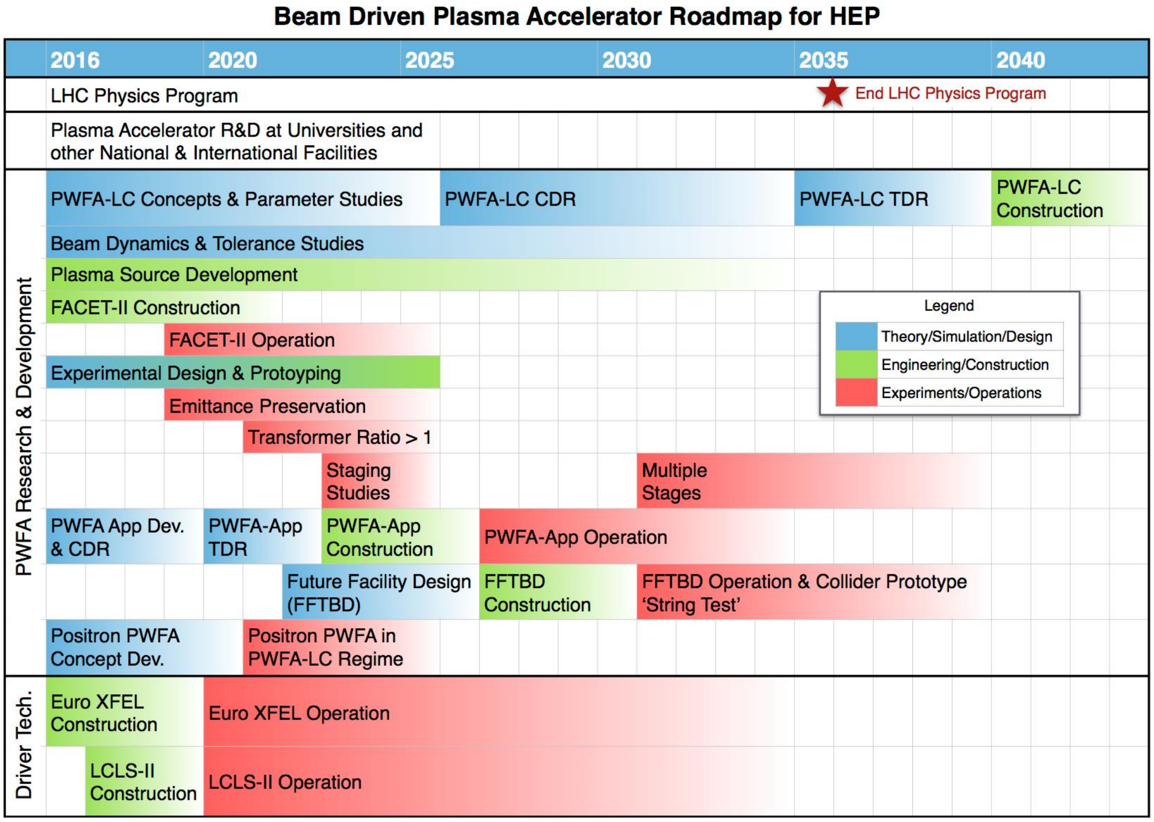
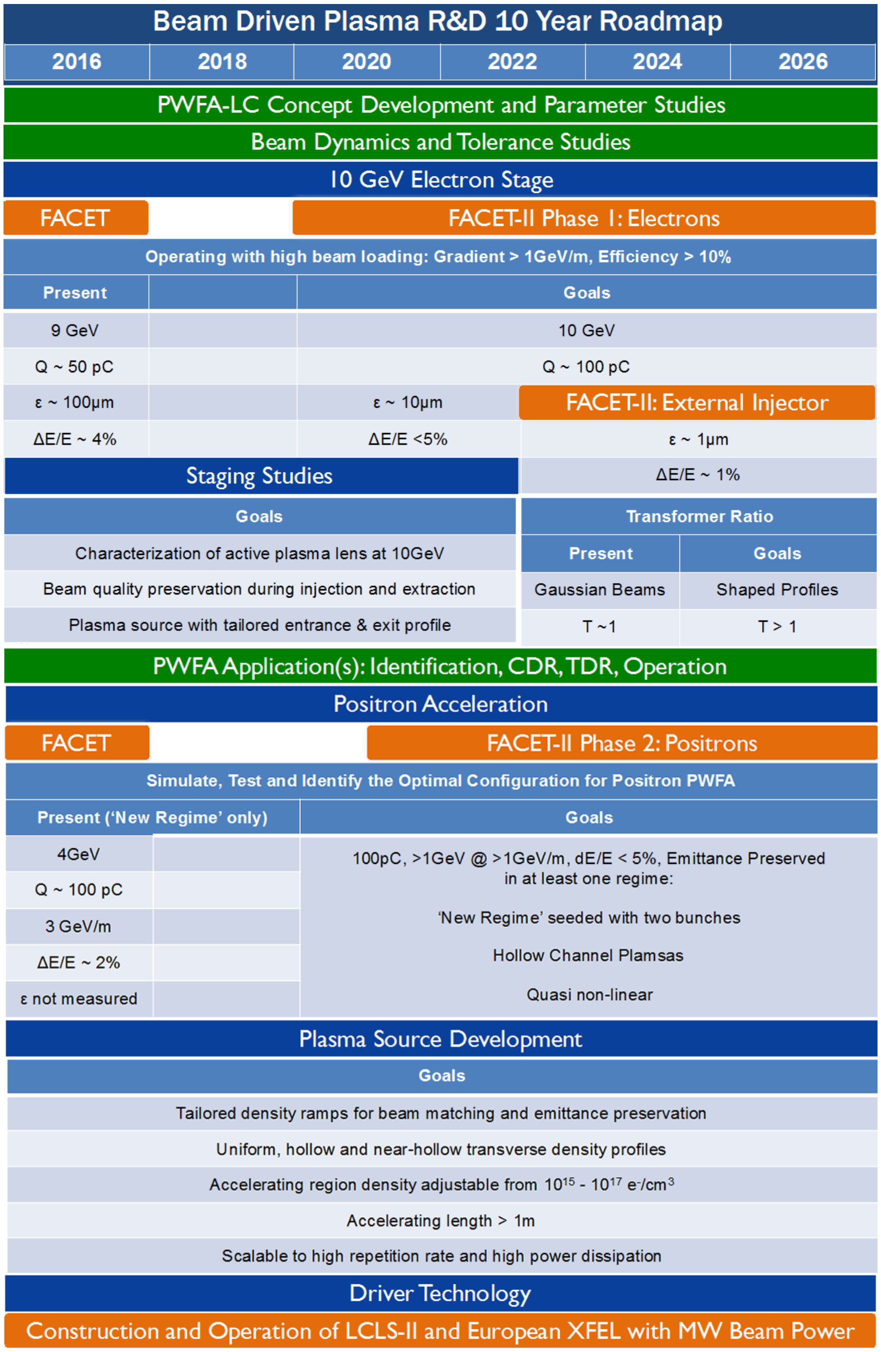


Figure 4: High level R&D roadmap for particle beam driven plasma accelerators.

The concepts for plasma accelerator based colliders should continue to be developed to help focus R&D. In addition, plasma accelerators are still in a period of rich discovery and a broad program of research at both Universities and National Laboratories should continue to ensure that the best techniques are identified. Some high level challenges common to all advanced accelerator concepts have been identified and summarized in the introductory portion of this document. The two areas of beam-plasma physics considered most pressing for research in the next decade are emittance preservation and positron acceleration. Additional priorities include beam loading, higher transformer ratios, beam dynamics & tolerances, plasma source development, staging, off-ramp, and first applications. A detailed roadmap for beam driven plasma wakefield accelerator R&D for the next decade is summarized in Fig. 5.



Beam Driven Plasma R&D 10 Year Roadmap

2016	2018	2020	2022	2024	2026

PWFA-LC Concept Development and Parameter Studies

Beam Dynamics and Tolerance Studies

10 GeV Electron Stage

FACET

FACET-II Phase 1: Electrons

Operating with high beam loading: Gradient > 1GeV/m, Efficiency > 10%

Present		Goals	
9 GeV		10 GeV	
Q ~ 50 pC		Q ~ 100 pC	
ε ~ 100µm		ε ~ 10µm	FACET-II: External Injector
ΔE/E ~ 4%		ΔE/E <5%	ε ~ 1µm
			ΔE/E ~ 1%

Staging Studies

Goals
Characterization of active plasma lens at 10GeV
Beam quality preservation during injection and extraction
Plasma source with tailored entrance & exit profile

Transformer Ratio	
Present	Goals
Gaussian Beams	Shaped Profiles
T ~1	T > 1

PWFA Application(s): Identification, CDR, TDR, Operation

Positron Acceleration

FACET

FACET-II Phase 2: Positrons

Simulate, Test and Identify the Optimal Configuration for Positron PWFA

Present ('New Regime' only)		Goals
4GeV		100pC, >1GeV @ >1GeV/m, dE/E < 5%, Emittance Preserved in at least one regime:
Q ~ 100 pC		'New Regime' seeded with two bunches
3 GeV/m		Hollow Channel Plamsas
ΔE/E ~ 2%		Quasi non-linear
ε not measured		

Plasma Source Development

Goals
Tailored density ramps for beam matching and emittance preservation
Uniform, hollow and near-hollow transverse density profiles
Accelerating region density adjustable from 10^{15} - 10^{17} e^-/cm^3
Accelerating length > 1m
Scalable to high repetition rate and high power dissipation

Driver Technology

Construction and Operation of LCLS-II and European XFEL with MW Beam Power

Figure 5: A detailed PWFA R&D roadmap for the next decade.

Progress is most rapid when there is an interplay between experimentation, theory and simulation. The PWFA roadmap aims to investigate the key R&D challenges highlighted in the preparatory workshops in an order of phased complexity in line with the expected availability of experimental facilities such as FACET-II at SLAC. In addition, nearer term stepping stone applications should be developed on the way to an electron-positron collider for high energy physics. As plasma accelerators continue to mature, as first applications are brought online and as concepts move to the conceptual and technical design level, a technology demonstration facility will have to be developed and operated to fully inform these designs. The PWFA roadmap also makes note of the fact that over the next decade the technology for high power electron beam drivers is being industrialized and put into operation to supply megawatt-class high-energy electron beams for the LCLS-II and European XFEL X-ray free electron lasers.

The FACET facility has operated for the past five years as an Office of Science National User Facility allocating roughly 50% of the beam time towards investigating plasma wakefield acceleration. FACET will continue to operate until April 2016. In the past five years University-National Lab collaborations have used the high energy, high peak current electron and positron beams to demonstrate many important aspects of electron and positron acceleration in plasmas. These demonstrations form the knowledge basis that the R&D roadmap will progress from over the next decade. Operating in the non-linear blowout regime, PWFA has demonstrated acceleration of ~50 pC of electrons with gradients ~7 GeV/m for a maximum energy gain of 9 GeV, a total energy spread of 4% and with an efficiency >10% [5] [6]. In addition, a new regime for accelerating positrons in a plasma wakefield was discovered and shown to accelerate more than 100 pC of positrons at a rate of more than 3 GeV/m for energy gain of more than 4 GeV with an energy spread of less than 2% and an efficiency greater than 30% [7].

Emittance preservation during acceleration will be critical for nearly any application of PWFA, and especially so for colliders where low emittance beams are needed to produce the required luminosity for physics at the TeV-scale. While also operating as a Department of Energy Office of Science National User Facility, FACET-II will serve as a community resource enabling a collaborative program in PWFA development over the next decade. FACET-II will add capabilities in a phased approach with an experimental program starting in 2019 and continuing until approximately 2025. Phase 1 of FACET-II will provide low-emittance high peak-current 10 GeV electron beams produced by an LCLS style photo injector. Experiments will aim to characterize and limit the mechanisms for emittance growth while accelerating ~100 pC of electrons at high gradients (>GeV/m) and strong beam loading (<10% energy spread and >10% efficiency). Characterization of PWFA beams will require diagnostics to be developed with micron spatial resolution, femtosecond time resolution, and the ability to discriminate between the drive beam and the accelerated trailing beam.

An electron-positron collider is envisioned as a tool for precision physics at the TeV scale. In Phase 2, FACET-II will provide the only high-energy high peak-current low emittance positron beam in the world to experimental collaborations. Experiments will aim to bench mark simulation codes and compare and contrast the three candidate regimes (so far) for positron acceleration in plasmas: quasi-non linear, hollow channel, and the new regime discovered at FACET in 2015. In parallel to the electron acceleration experiments, these efforts will also work to characterize and limit the mechanisms for emittance growth while accelerating ~100 pC of positrons at >GeV/m, with more than 1 GeV of energy gain to identify the optimal configuration for plasma acceleration of positrons for collider applications.

Staging multiple plasma cells together to reach very high energies will likely be involved in any collider application. At FACET-II, an independent witness beam injector will be used to understand the tolerances for merging and extracting beams with different energies into and out of a plasma stage. The knowledge gained from these experiments will pave the way for designing systems with multiple plasma stages to reach progressively higher energy. Correctly shaped beam current profiles are predicted to produce higher efficiency and beam loading with correspondingly higher electrical efficiency, smaller final energy spread and a larger transformer ratio (larger energy boost per stage and efficiency). Current experiments work with Gaussian current profiles and transformer ratios of one or less. The flexibility of independent drive and witness beams will allow for independently shaping the current profiles of the different beams. Experiments will provide an understanding of how much greater than one the practical transformer ratio can be while still preserving beam quality.

The transport and focusing of particle beams into and out of the plasma stage must be carefully managed to preserve the beam emittance. A recent theoretical framework describes a mechanism for accomplishing this by adjusting the plasma density transitions at the entrance and exit of the plasma cell [8]. Development of suitable plasma sources will be essential to the demonstration of emittance preservation in plasma accelerators. Hollow or nearly hollow channel plasmas have been proposed as a candidate regime for positron acceleration. Some recent experiments have demonstrated a form of hollow channel free of plasma on axis [9]. Future experiments will require an even greater degree of control, and plasma source development must proceed hand-in-hand with every experimental program. In addition, the footprint of a collider and the geometric (effective) accelerating gradient will depend on the distance between successive plasma accelerating stages. So-called active plasma lenses [10] have demonstrated strong focusing that may aid matching high energy beams between plasma cells and reduce the inter-stage distance [4]. Characterization of such lenses with high peak current, low emittance 10 GeV beams will allow for a much greater understanding of their utility in collider applications.

The roadmap indicates that the first applications for PWFA will be explored within the next decade. The exact nature of the first application is still to be determined, but candidates ranging from high intensity gamma ray beams for nuclear physics or a new generation of X-ray free electron lasers have been discussed. The development of any PWFA application will drive tolerance and systems engineering studies that will feed into future collider designs. This level of design effort will drive development of enhanced simulation capabilities. Hardware and software developments will reduce the timeframe for detailed simulations from weeks to hours or even minutes. By providing rapid turnaround time, high resolution with full physics packages enabled, simulations will make great strides and transition from powerful tools used to understand our experiments to tools used to design and optimize experiments with fidelity. Integration with traditional accelerator codes will also greatly enhance the utility of plasma codes for numerical design and prototyping of collider systems.

DWFA Roadmap and Milestones

The primary objective of the Advanced Accelerator R&D (AARD) Group at Argonne is to develop Dielectric Wakefield Accelerator (DWFA) enabling technologies for a multi-TeV class e^+e^- Linear Collider (LC). In the past five years, the Argonne Wakefield Accelerator (AWA) facility was transformed into a flexible, state-of-the-art LC testbed. Our scheme, dielectric Two Beam Acceleration (dielectric TBA), is based on low-cost dielectric structures operating at gradient of 300 MeV/m and powered by gigawatt-scale, short RF pulse (20 ns) which is derived from the AWA high-current drive beam. On the road to the development of a LC, we are also applying DWFA technologies to other application**s** as well as synergistically supporting other advanced accelerator concepts.

In the four subsections below, we present the roadmap and main milestones of DWFA technologies from 2016 to 2026. Note that a total of seven critical technology elements (CTEs) were identified for the DWFA LC design:

- CTE1: polarized e^+ source at the full LC operational parameters including damping ring;
- CTE2: polarized e^- source at the full LC operational parameters including damping ring;
- CTE3: main beam acceleration;
- CTE4: drive beam power source;
- CTE5: staging of multiple acceleration structures to high energy;
- CTE6: beam delivery system; and
- CTE7: appropriate main-beam parameters at the IP.

Each CTE was scored on its technical readiness level (TRL) ranging from TRL1-9 adopted from the DOE Technology Readiness Assessment Guide (DOE G 413.3-4A). Four of the CTE's (1, 2, 6 and 7) are already at TRL4 since they were taken from the CLIC or ILC designs due to their similarities with our scheme while the other three CTE's (3, 4 and 5) will be brought TRL4 by the Argonne group.

The core mission of the AARD group at Argonne is to bring all CTE's to TRL4 in the next 5 years and CTE's 3, 4 and 5 to TRL5 in the subsequent 5 year period by carrying out an integrated experimental research program at the AWA facility.

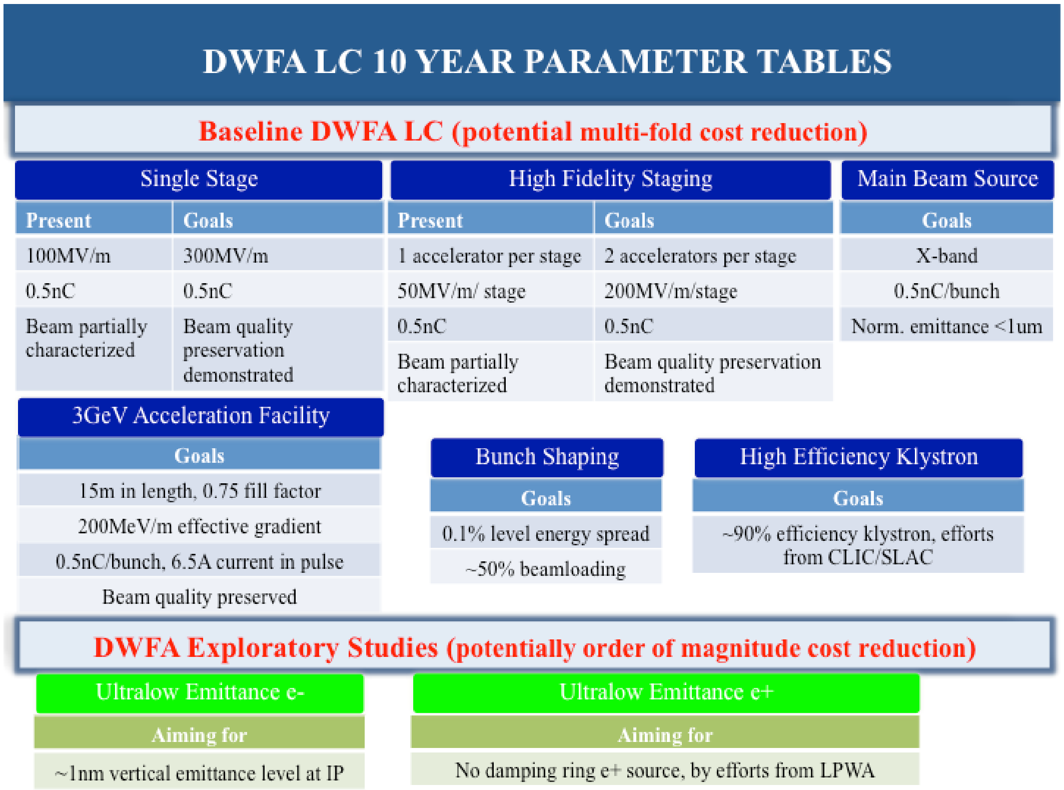
DWFA LC Baseline Technology

The baseline DWFA LC uses short RF pulse, dielectric TBA as the main linac for both electron and positron acceleration. With a target gradient of 300MV/m (effective gradient 200MV/m), low-cost dielectric structures, and a simple drive-beam based power source, main bunch shaping to raise the efficiency, and high efficiency klystrons, the baseline DWFA scheme has the potential for a multi-fold reduction in cost compared with current LC technology.

Prior to the commissioning of the new AWA facility in 2015, the gradient achieved in the TBA scheme was modest (<10MV/m) and staging had not been demonstrated. By the beginning of 2016, it had reached a gradient of 100MV/m in a single TBA module, 50MV/m for two-staged TBA, and a single bunch of 0.5nC was accelerated in both cases with the beam quality preserved. Rapid progress is expected to continue in the next five year period as the newly commissioned AWA facility has only recently begun to be exploited.

As shown in Fig. 6, in the first five year period (2016-2021), the baseline DWFA will primarily focus on the technology consolidation phase with the goal of elevating all CTE's to TRL4. Specifically, we aim to extract GW level RF power from the AWA drive beam (CTE4) in order to boost the gradient to 300MV/m in a single TBA module (CTE3). Further, we plan to demonstrate high-fidelity, two-stage acceleration which contains a beam kicker, RF delay lines, and two TBA modules per stage. Demonstration of staging is meant to show that the baseline DWFA scheme is scalable to a TeV-class LC (CTE5).

In the following five year period (2021-2026), the baseline DWFA will enter the technology integration phase. With CTE's 3, 4, and 5 all brought to TRL4 during the first five year period, as described above, we next plan to integrate the independent technologies of these the independent CTE's into a high-fidelity, integrated, TRL5-level, dielectric TBA test facility. This test facility will simultaneously deliver high-gradient, staging, and acceleration of a linear collider quality beam. With additional funding, an X-band e^- source to demonstrate operation at beam currents relevant to an operational LC would be developed. At that point, all three CTEs are secured at TRL5. Depending on the need, this technology could be ready for a ~5 GeV stepping stone facility at the end of this ten year period. The technical goals are summarized in Fig. 6.



DWFA LC 10 YEAR PARAMETER TABLES

Baseline DWFA LC (potential multi-fold cost reduction)

Single Stage	
Present	**Goals**
100MV/m	300MV/m
0.5nC	0.5nC
Beam partially characterized	Beam quality preservation demonstrated

High Fidelity Staging	
Present	**Goals**
1 accelerator per stage	2 accelerators per stage
50MV/m/ stage	200MV/m/stage
0.5nC	0.5nC
Beam partially characterized	Beam quality preservation demonstrated

Main Beam Source
Goals
X-band
0.5nC/bunch
Norm. emittance <1um

3GeV Acceleration Facility
Goals
15m in length, 0.75 fill factor
200MeV/m effective gradient
0.5nC/bunch, 6.5A current in pulse
Beam quality preserved

Bunch Shaping
Goals
0.1% level energy spread
~50% beamloading

High Efficiency Klystron
Goals
~90% efficiency klystron, efforts from CLIC/SLAC

DWFA Exploratory Studies (potentially order of magnitude cost reduction)

Ultralow Emittance e-
Aiming for
~1nm vertical emittance level at IP

Ultralow Emittance e+
Aiming for
No damping ring e+ source, by efforts from LPWA

Figure 6: Present status and goals for DWFA LC parameters.

Technical Challenges

The technical challenges for achieving the DWFA roadmap milestones are significant and can broadly be divided into three technological areas: “structures”, “drive beam”, and “RF power”. DWFA LC is based on a modular design and its most fundamental building blocks are the structures: the dielectric power extractors and the dielectric accelerators. DWFA structure development comprises one of the primary areas of concentration. In the past, the DWFA program has developed numerous technologies required for accelerating structures, including: dielectric structure frequency tuning, transverse wakefield damping, RF breakdown mitigation, broadband impedance matching, multipactor suppression, etc. In the next phase, focus will be on developing full-featured, dielectric structures that integrate all of these technologies, and then begin testing at higher gradients and higher power. The construction of four dielectric structures began in 2016 and our effort will be focused on continual improvement of the structure’s readiness level.

Drive beam production and transportation are keystone technologies needed for the DWFA LC scheme. The drive RF photoinjector (Cs2Te) beam line was commissioned in 2015 and now routinely operates at 70 MeV and is capable of various bunch train formats ranging from 8x80nC to 16x40nC including a record total train charge of 660 nC. Recent efforts are now focused on improving the stability of high charge operation and the uniformity of the drive bunch train in order to test the TBA scheme (and others) at higher power and gradient. AWA is currently developing the challenging beam line optics needed to deliver the drive beam through the dielectric power extractors. This beam line must deliver a stable drive beam through multiple stages of acceleration as it continuously loses energy. At the same time, the number of beam line elements must be kept small in order to maximize the effective gradient.

Gigawatt-level RF power is needed to establish >300 MV/m gradient in DWFA accelerators. The AWA drive beam contains ~5 GW beam power and frequency content covers up to W-band. High-frequency RF pulses, on the level of hundreds of MW, can be generated with the AWA drive beam. In a recent experiment, RF pulses of approximately 100MW, X-band, 10ns, were generated at the AWA facility. However, to reach the GW level, more work needs to be done, including the development of RF components capable of transporting GW-level, short RF pulse, techniques for low-loss RF transportation, techniques for RF phase control, etc.

In summary, the AWA facility at Argonne has been specifically designed to address the key technologies presented above. With balanced resources the milestones on the path of the DWFA LC 10-year roadmap can be achieved.

DWFA Exploratory Technology

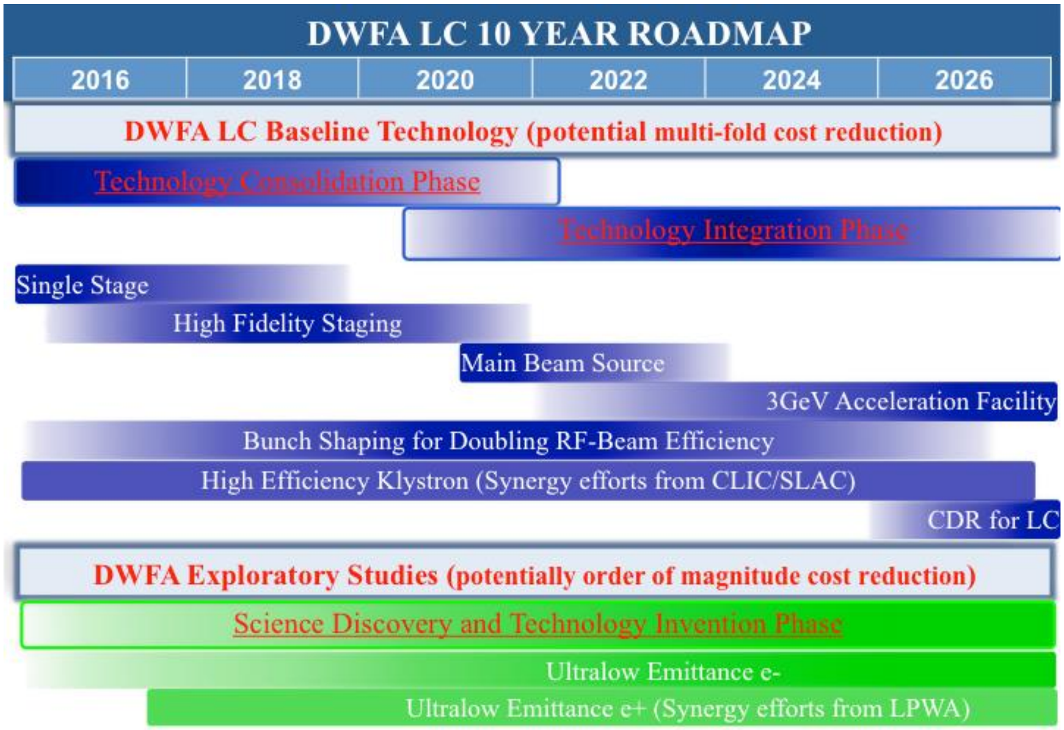
Parallel to the DWFA LC baseline R&D program, two other research directions will be pursued over the next ten years (see Fig. 7):

- The first effort, to increase the efficiency, has relatively high probability of success and could reduce the site power by about a factor of two.
- The second effort, ultra-low emittance, could reduce the site power even more dramatically but it is a more speculative approach (i.e. high-risk, high-reward).

If either one of these efforts succeeds then the LC landscape will be transformed.

A high wall plug efficiency (>10%) is highly desirable for a TeV class LC in order to reduce site power. Given that the baseline LC requires a beam power of approximately 30 MW to achieve the needed luminosity and a wall plug efficiency of 7.5%, then the required site power would be about 400 MW. In the calculation of the total efficiency, the RF-to-beam efficiency (~26% in the baseline design) is one component in the efficiency chain. Instead of using the usual Gaussian e^- and e^+ distribution (as in the baseline), a longitudinally shaped bunch can be used to increase the beam loading which, in turn, can double the RF-to-beam efficiency. The first shaped bunch was demonstrated using the AWA emittance exchanger beam line in 2015 and this will be used to study its application to heavy beam loading to increase efficiency. Coupled with the recent research into high efficiency klystrons (>90%) at SLAC/CLIC, the site power could be reduced by greater than a factor of two reducing the site power in the baseline to 200MW. This research is estimated to have a high probability of success.

The dependence of luminosity on beam power and emittance shows that for the same luminosity the beam power can be reduced by a factor of three to five, if the beam's vertical emittance is reduced from the current level (tens of nanometer) level down to 1nm. The approach to reduce e^- emittance is based on various phase space manipulation efforts (e.g. emittance exchange) and reduction of source emittance (see the section titled "Other Applications"). The ultra-low emittance e^- beam, if coupled with an ultra-low e^+ beam (synergy with the BELLA ultra-bright e^+ source), has the potential to cut the overall cost of the LC by an order of magnitude.



Note: the color fading is proportional to the effort. Timeline is subject to funding level. Cost reduction compared to current LC technology

Figure 7: DWFA ten year roadmap.

Other Applications

A ten year roadmap for DWFA applications can be found in Fig. 8. Thanks to the advantage of DWFA technology in terms of low cost (construction and operation), demonstrated high-gradient (>100MeV/m) and potential for high-repetition rates (~MHz), the technology offers a promising approach for a next generation XFEL light source. Theoretical studies and end-to-end numerical simulations had been performed and published. In the next five year period (2016-2021), AWA will continue the effort and begin fabrication in order to demonstrate a meter-scale DWFA module, provided that the financial support is available. The goal is to advance DWFA XFEL design to Technical Readiness Level 4 by 2021 so that a CDR can be written if needed. The expertise gained in this effort (e.g. dielectric structure fabrication) would have a direct benefit toward the DWFA LC baseline R&D program.

In 2016, the Matter-Radiation Interactions in Extremes (MaRIE) project by Los Alamos National Laboratory started collaboration with the AWA group to develop an ultrahigh brightness electron source for MaRIE project. The joint efforts will benefit the DWFA LC exploratory effort in its development of an ultra-low emittance e^- source.

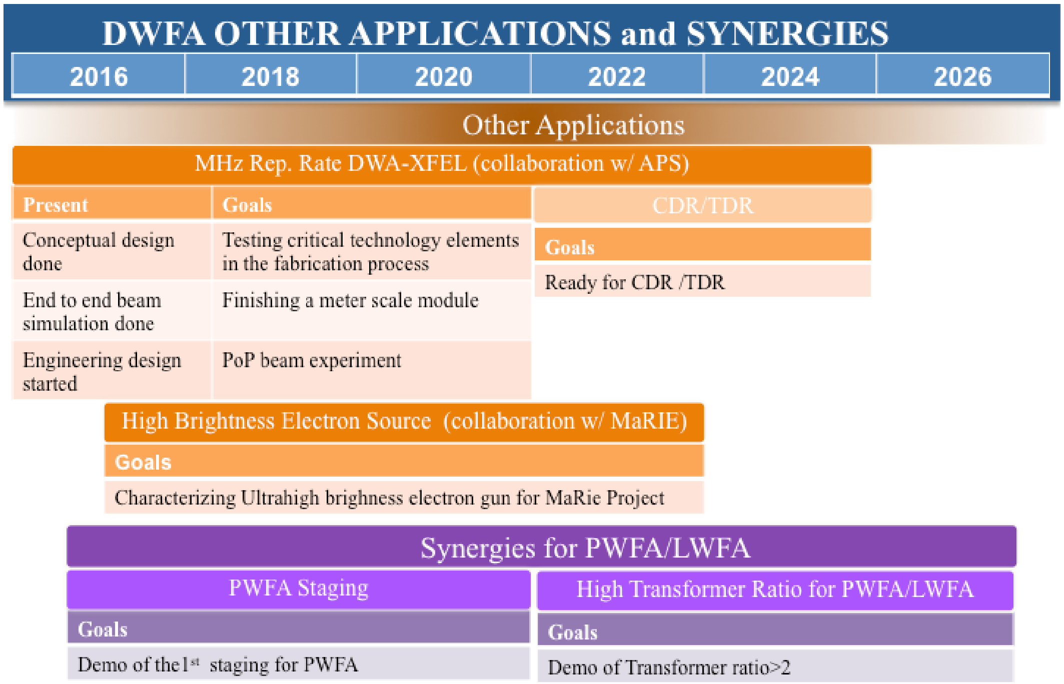


Figure 8: DWFA application development and synergies ten year roadmap.

Synergies

Extensive collaboration among the three LWFA, PWFA, and DWFA concepts over the next ten years would be highly beneficial to all AAC programs in DOE. As discussed below, the technical overlap between LWFA and PWFA suggests a number of collaborative avenues. In addition, the facilities supporting DWFA research and development can inform many of the issues facing future wake-field colliders.

The roadmaps for the plasma-based approaches, LWFA and PWFA, contain many similarities and parallels, since much of the physics and required R&D are independent of the driver. These parallels include the multiple staging of ~1-10 GeV level modules, the preservation of beam quality throughout multiple stages, mitigation of emittance growth due to collisions and ion motion, high efficiency acceleration, the difficulty of accelerating positrons with nonlinear plasma waves, the use of hollow plasma channels for positron acceleration, and the mitigation of transverse beam instabilities. The overarching goals of the plasma-based R&D roadmaps include: a) solving the outstanding physics issues through experimental investigations and simulations so that the potential of plasma–based colliders can be realistically considered; b) addressing through experiments and computer simulations engineering issues such as tolerances; c) continuously refining a collider design based on the latest data from experiments and simulations; and d) developing driver technologies that will enable the demonstration of a real multi-stage plasma accelerator at the requisite repetition rate. The plasma-based roadmaps show that there is a considerable agreement between the proponents of LWFA and PWFA as to what the outstanding physics issues are and a rough timetable for the required R&D. Progress may be faster if some of these issues were addressed at either the BELLA or the FACET-II facility as appropriate as long as they are common to both schemes. For instance, developing various ideas for high quality positron acceleration may in the next five years be better suited for

FACET-II whereas staging and tolerance studies might be more rapidly done at BELLA. As another example, in the near term, active plasma lenses, recently demonstrated at LBNL [10] at the 100 MeV level can be tested at ATF at BNL with very well characterized electron beams, at the multi-GeV level at BELLA and/or at FACET-II. Also, plasma source development will be beneficial to all plasma based schemes and is an area where cooperation and sharing of technology can occur. A continuous dialogue is the key to most optimum planning and the return on DOE's investment in this arena.

The AWA facility offers synergistic opportunities with plasma based acceleration with a world-class, high-power electron beam; a bunch shaping beam line; two independent electron sources; and a spacious experimental area. The staging and bunch shaping for high transformer ratio capabilities mean that the facility can be used to demonstrate these critical technology elements for both PWFA and LWFA technologies. As shown in Fig. 8, the AWA facility can be used as the platform to test these technologies for plasma schemes. Further critical technology elements can also be tested (e.g. external injection based on the Trojan Horse) provided support for a multi-pass laser amplifier is made available.

Resource Requirements for Simulation

As indicated in the previous sections, each of the AAC concepts will require continued simulation support and improvement to progress. The infrastructure underpinning the simulation efforts will require sustained commitment to: a) development of personnel and computational teams; b) development of new multi-scale models and algorithms; and c) exploitation of new architectures.

The development of simulation tools needed for the design of an advanced multi-TeV collider requires robust and sustained team efforts. Teams will consist of individuals with varying skills and responsibilities: code builders, maintainers, and users. Members should have combined expertise in physics, applied math, and computational science. A multiple team approach has many benefits, allowing for cross-checking of results and pursuit of varied approaches.

The path to real-time simulation of staged acceleration involves development of multi-scale models and algorithms and, at the same time, use of emerging parallel computer architectures. These are generally not core topics in the graduate physics curriculum. The community will have to provide the required education, not just for code builders but also for code users and anyone who has to interpret simulation results. Education can no longer be exclusive to those who will develop codes. Further, because of the rapid developments in computation, current text books are out of date. They need updating to include description of new processors, algorithms, and methods for data handling.

The community faces a challenge in making use of new computer architectures. Emerging Exascale architectures support three levels of parallelism: distributed memory parallelism, shared memory parallelism, and vectorization. Efficient use of such computers requires effective use of all three levels. However, existing codes are generally written with a single architecture in mind, and are not ported rapidly enough. Further, some of the unique algorithms are very hard to port due to data structure differences (different data structures required by particles, fields, and collisions). The community must develop data structures and methods that are flexible enough for all processors will encourage the adoption of data standards. Open sources for modules, algorithms, and codes must be developed and shared. Finally, local computing sources, greatly improve development time by eliminating queues.

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Appendix A: Charge to the Workshop

DOE Advanced Accelerator Concepts Research Roadmap Workshop
Hilton Gaithersburg
620 Perry Parkway
Gaithersburg, MD 20877
February 2–3, 2016

Dear Colleagues,

This workshop is organized in response to the recently released HEPAP Accelerator R&D Subpanel Report, "Accelerating Discovery—A Strategic Plan for Accelerator R&D in the U.S." (available at http://science.energy.gov/~/media/hep/hepap/pdf/Reports/Accelerator_RD_Subpanel_Report.pdf), which contains the recommendation to "Convene the university and laboratory proponents of advanced acceleration concepts to develop R&D roadmaps with a series of milestones and common down-selection criteria towards the goal of constructing a multi-TeV e^+e^- collider."

The goal of the workshop is to develop a research roadmap for the advanced accelerator concepts within the HEP General Accelerator R&D (GARD) program. The three advanced accelerator concepts (AAC) deemed to have potential for future high energy collider applications are the dielectric wakefield accelerator (DWFA), the laser-driven plasma wakefield accelerator (LWFA) and the particle-beam-driven plasma wakefield accelerator (PWFA). Prior to this workshop, each of the concepts has conducted its own preparatory workshops to generate a preliminary roadmap with a list of prioritized milestones to be used as input to this workshop, where they will be discussed, adjusted as needed and integrated into one unified roadmap for this GARD research thrust. For efficiency consideration and for the benefit of those attending this workshop, we ask that the leaders of these preparatory workshops (Wei for DWFA, Wim for LWFA, and Mark for PWFA) provide reading material (documents or website links) to the attendees by January 25, 2016. This will help them prepare for discussion at the workshop.

It should be noted that this workshop is not a review of the research programs or their potential conceptual designs, but rather a strategic formulation undertaking to generate a set of milestones to be assembled as part of a research roadmap to guide the GARD-AAC activities over the next 5-10 years. These milestones should provide appropriate criteria for possible down-selection along the way.

As you construct the roadmap, please prioritize the milestones to align with what you think are the most pressing challenges that need to be addressed to move the field toward the HEP collider application. For each concept, you should consider the most sensible sequence for these research activities, such as:

- Achieving a minimum geographic accelerating gradient,
- Achieving higher energy by staging multiple modules,
- Achieving a target level of emittance preservation,
- Achieving relevant beam currents,
- Achieving a target power efficiency,
- Controlling beam instabilities,
- Developing suitable electron and positron sources,
- Developing specialized ancillary systems for a collider (e.g. final focus optics),
- Developing associated supporting technology (e.g. power sources), and

- Potential early applications within or beyond HEP.

Consideration should also be given to needed developments in other underlying accelerator science areas such as beam physics, computer modeling and simulation, beam instrumentation and diagnostics, and test facilities, which are critical for supporting the successful development of these advanced concepts. The milestone plan should exploit synergies between these different concepts and other international research efforts in this field.

The final product of this workshop is a 10-year comprehensive research roadmap for the DOE-AAC program, complete with a prioritized list of milestones together with justification and explanation for their selection.

Thank you for agreeing to participate in this workshop. Your contribution to the development of this research roadmap is very important for the success of the advanced accelerator concepts thrust within the HEP-GARD program.

Sincerely,

Dr. L.K. Len
DOE Office of High Energy Physics

Appendix B: Agenda and List of Participants

Agenda

Tuesday, February 2, 2016		
Time	**Speaker**	**Title**
8:30 AM	Jim Siegrist/Glen Crawford	Welcome and Opening Remarks
8:45 AM	L.K. Len	GARD Overview and Workshop Objectives
9:30 AM	W. Gai / C. Jing	DWFA preparatory workshop report
10:30 AM	***Break***	
10:45 AM	W. Gai / C. Jing	DWFA Research Roadmap and Milestones
11:30 AM	W. Leemans / C. Schroeder	LWFA preparatory workshop report
12:30 PM	***Lunch***	
1:30 PM	W. Leemans / C. Schroeder	LWFA Research Roadmap and Milestones
2:15 PM	M. Hogan / M. Litos	PWFA preparatory workshop report
3:15 PM	***Break***	
3:30 PM	M. Hogan / M. Litos	PWFA Research Roadmap and Milestones
4:15 PM	All	Round Table Discussion
5:15 PM	***Adjourn***	

Wednesday, February 3, 2016		
Time	**Speaker**	**Title**
8:30 AM	C. Joshi	Potential synergy between LWFA and PWFA
9:00 AM	J. Rosenzweig	Potential synergy between DWFA and PWFA
9:30 AM	A. Seryi	Potential synergy with global efforts
10:00 AM	I. Ben-Zvi	Off-ramp for potential early applications
10:30 AM	***Break***	
10:45 AM	M. Downer	Diagnostics needs
11:15 AM	T. Antonsen	Simulation needs
11:45 AM	S. Nagaitsev	Beam issues and challenges
12:15 PM	***Lunch***	Discussion
1:15 PM	G. Blazey + All	Research roadmap integration and discussion
3:15 PM	***Break***	
3:30 PM	G. Blazey + All	Research roadmap--discussion of priorities and milestones
5:00 PM	All	Finalize GARD-AAC Research Roadmap
5:30 PM	***Adjourn***	

Invited Participants

Thomas Antonsen	*University of Maryland*
Ilan Ben-Zvi	*Brookhaven National Laboratory*
Jerry Blazey	*Northern Illinois University*
Yunhai Cai	*SLAC National Accelerator Laboratory*
Weiren Chou	*Fermi National Accelerator Laboratory (retired)*
Michael Downer	*University of Texas-Austin*
Wei Gai	*Argonne National Laboratory*
Carl Schroeder	*Lawrence Berkeley National Laboratory*
Mark Hogan	*SLAC National Accelerator Laboratory*
Chungguang Jing	*Argonne National Lab/Euclid Techlab*
Chan Joshi	*University of California-Los Angeles*
Wim Leemans	*Lawrence Berkeley National Laboratory*
Michael Litos	*SLAC National Accelerator Laboratory*
Sergei Nagaitsev	*Fermi National Accelerator Laboratory*
James Rosenzweig	*University of California-Los Angeles*
Andrei Seryi	*John Adams Institute*
Bill Weng	*Brookhaven National Laboratory*

Other Participants

L.K. Len (DOE)

J. Siegrist (DOE)

G. Crawford (DOE)

J. Boger (DOE)

E. Colby (DOE)

K. Marken (DOE)

A. Lankford (HEPAP)

V. Lukin (NSF)