

PREPARED FOR SUBMISSION TO JINST

SPECIAL ISSUE:

ICFA BEAM-DYNAMICS NEWSLETTER #83

## US Advanced and Novel Accelerator Beam Test Facilities

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**ABSTRACT:** Demonstrating the viability of Advanced Accelerator Concepts (AAC) relies on experimental validation. Over the last three decades, the US has maintained a portfolio of advanced and novel accelerator test facilities to support research critical to AAC. The facilities have enabled pioneering developments in a wide variety of beam and accelerator physics, including plasma-wakefield and structure-wakefield acceleration. This paper provides an overview of the current portfolio of US facilities possessing charged particle drive beams with high energies, on the order of tens of joules per pulse, or drive lasers with high peak powers, on the order of a petawatt, and are actively conducting AAC research.

**KEYWORDS:** Only keywords from JINST's keywords list please

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This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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## 1 Introduction

In the United States, the accelerator research and development (R&D) program is sponsored by the Department of Energy (USDOE) Office of Science [1] and the National Science Foundation (NSF) [2]. The program pursues fundamental accelerator research and develops accelerator technology and methods to increase beam brightness, accelerating gradient, average power, etc., to dramatically improve the cost effectiveness and performance of accelerators [3]. This program is key to creating accelerator user facilities in the mid- and far-term for discovery science (particle physics, neutron sources, light sources, etc.) and to create near-term, low-cost, compact accelerator technology available for future societal applications in the medical, security, and industrial fields. The US Advanced and Novel Accelerator (ANA) beam test facilities are crucial components for advancing accelerator science and technology (S&T).

## 2 ANA Beam Test Facilities Mission

The mission of the US ANA beam test facilities is to provide the experimental test beds where fundamental accelerator research can be explored and novel accelerator technology can be developed and undergo integration testing. In addition to this S&T mission, ANA beam test facilities are where many of the future scientists and engineers needed by the accelerator community are educated and trained [4, 5]. At the highest level, the mission of the facilities can be broken down as:

1. Providing experimental test beds to carry out basic research in advanced accelerators and beam physics.
2. Developing the S&T needed to enable the next generation of science facilities and accelerator applications.
3. Educating and training future scientists and engineers.

## 3 ANA Beam Test Facilities

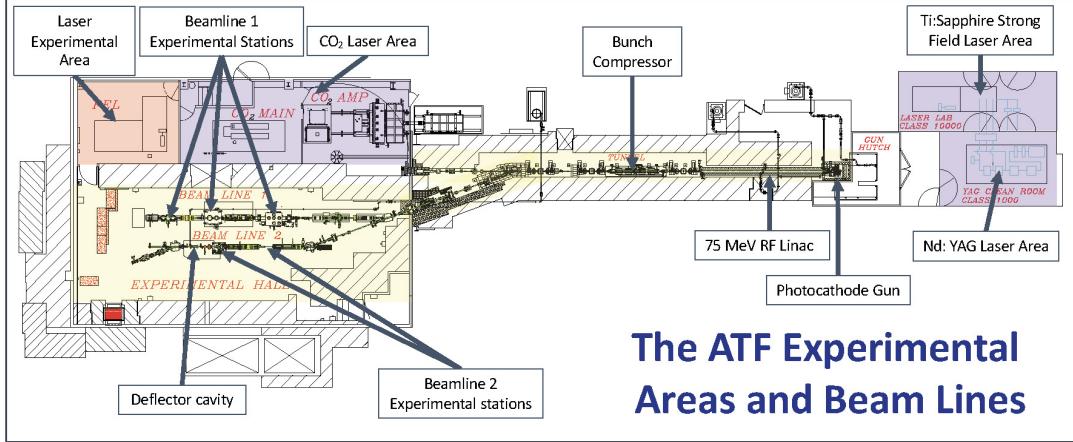
The above mission is carried out at several beam test facilities located at US National Laboratories and Universities. In this section, a list of large beam test facilities that are equipped with high-power drive beams (electron or laser) and are currently engaged in advanced accelerator R&D is given, with an accompanying overview of each research program. Note, this list is not exhaustive as it leaves out many university-scale beam test facilities due to space limitations. We note that these facilities are vital to AAC research since this is where many ideas are first developed before being tested on a larger scale.

### 3.1 National Laboratories

#### 3.1.1 The Accelerator Test Facility (ATF) at Brookhaven National Laboratory

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory serves the US DOE Accelerator Stewardship program and develops advanced acceleration methods for leptons and ions as well as high-energy photon sources. The ATF provides access to three classes of experimental

facilities: a long-wave infrared high-power laser at  $9.2\text{ }\mu\text{m}$ , a high-brightness linac-driven 75-MeV electron beam, and near-IR laser sources. This combination of capabilities enables programs on particle and photon source development, wakefield acceleration, inverse Compton scattering, and laser-driven plasma ion acceleration.



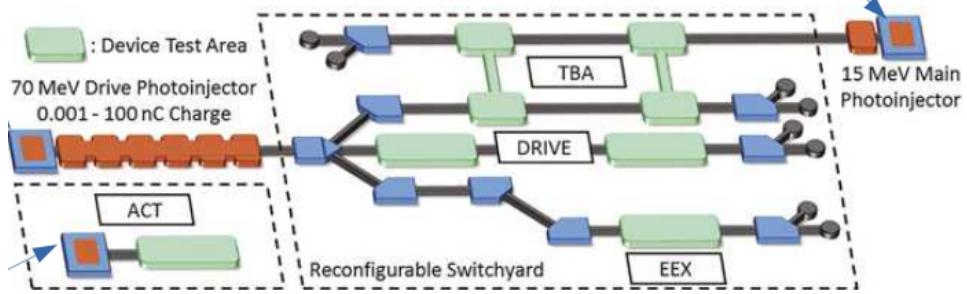
**Figure 1.** Overview of the ATF facility. User experiments can be configured to utilize the near-IR laser beams, long-wave IR beam, and electron beam singly or in any combination.

### 3.1.2 The Argonne Wakefield Accelerator (AWA) at Argonne National Laboratory

The Argonne Wakefield Accelerator (AWA) Facility [6] is dedicated to the investigation of Structure Wakefield Acceleration (SFWA) including both collinear wakefield acceleration (CWA) and short-pulse two-beam acceleration (TBA). The AWA facility (Fig. 2) consists of three accelerators: the Drive Photoinjector (producing up to 70-MeV high-charge electrons), the Main Photoinjector (which forms 15-MeV electron bunches), and a few MeV cathode test-stand. AWA research focuses on underlying beam-dynamics challenges (e.g., production of bright- and high-charge-beams), beam manipulation (e.g., beam-current shaping) and beam control (e.g., mitigation of the BBU instability), and the development of advanced accelerating structures (e.g., dielectric waveguides, planar structures, metamaterials, rapid filling metallic structures, etc.) for efficient, high-peak-power RF generation and high-gradient acceleration. AWA has demonstrated unprecedented beam-transformer ratios ( $> 5$ ) in both SWFA and Plasma Wakefield Accelerator (PWFA) setups. Likewise, it has generated GW-scale peak-power RF-pulses and demonstrated staging in a TBA configuration in the pursuit of a linear collider. AWA develops these technologies for other applications (FELs and compact accelerators) and synergistically supports other advanced-accelerator concepts.

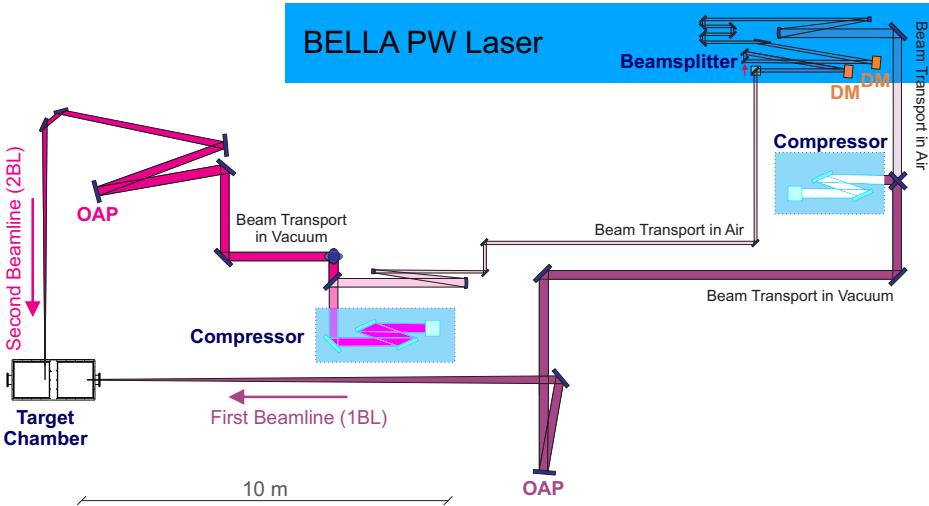
### 3.1.3 The Berkeley Lab Laser Accelerator (BELLA) Center at Lawrence Berkeley National Laboratory

The BELLA Center at LBNL has been performing research on laser-plasma accelerators (LPAs) for over two decades. The main research objectives are the development of LPA modules at the 10 GeV level and the staging (coupling) of LPA modules, which are two essential R&D components for a future plasma-based linear collider. The current laser systems at the BELLA Center include



**Figure 2.** Overview of the AWA facility consists of a 70-MeV drive-beam photoinjector, a 15-MeV main-beam photoinjector, and the Argonne cathode test-stand (ACT).

the BELLA Petawatt (PW) laser and two independent 100 Terawatt (TW) laser systems. Upgrades are underway to the BELLA PW beamline to allow the delivery of two synchronized pulses, with independent compressors, on target, enabling staging, and a short focal length capability, enabling experiments at ultrahigh intensity (Fig. 3). The BELLA Center is also pursuing a new facility, kBELLA, consisting of a 1 kHz, few J, 30 fs, high average power laser for the demonstration of a high rep-rate, precision LPA and subsequent applications. The BELLA Center functions as a collaborative research center and is part of LaserNetUS [7].



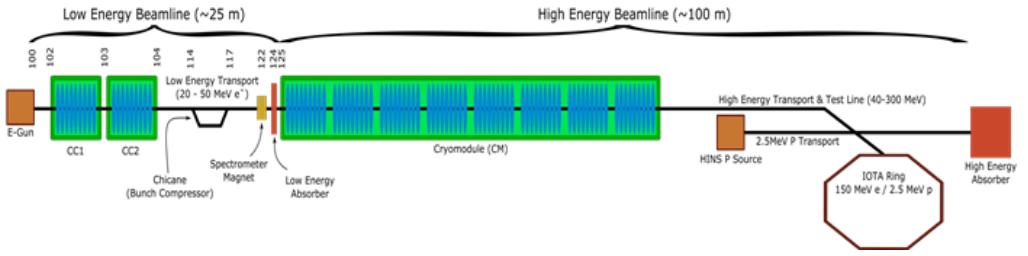
**Figure 3.** Schematic of the two beamline configuration on the BELLA PW laser.

### 3.1.4 The Fermilab Accelerator Science and Technology facility (FAST) at Fermi National Accelerator Laboratory

The facility (Fig. 4) consists of a storage ring, IOTA, capable of operating with both protons and electrons with beam momentum range 50-150 MeV/c and two injector linacs (electrons and protons). The IOTA research goals are mostly focused on the challenges, posed by future high-intensity machines, such as beam instabilities and losses. The IOTA storage ring is unique in its flexibility and performance. It has a circumference of 40 m and a relatively large aperture (50

mm). It is easily reconfigurable to accommodate the installation of 1-3 concurrent experiments. The focusing lattice was designed to have significant flexibility to enable a wide variety of studies. The IOTA proton injector produces beam at a fixed energy of 2.5 MeV (kinetic), while the energy output of the electron linac can be varied up to 300 MeV. Research with electron beams into optical stochastic cooling is underway at both IOTA (Fermilab) and CESR (Cornell).

More specifically, the IOTA research program aims to push the maximum beam intensity and brightness of future ring accelerators while minimizing the accelerator scale and cost. Along this direction, the key research areas are i) suppression of coherent beam instabilities by Landau damping; ii) mitigation of space-charge effects, and iii) beam cooling. The main candidate technologies being pursued at IOTA are the Nonlinear Integrable Optics, Electron Lenses, and Optical Stochastic Cooling.



**Figure 4.** Layout of the FAST facility.

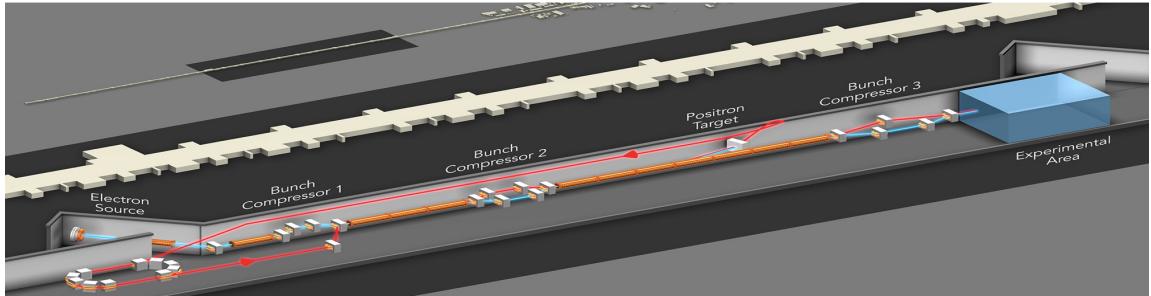
### 3.1.5 The Facility for Advanced Accelerator Experimental Tests II (FACET-II) at SLAC National Accelerator Laboratory

This facility is an upgrade of the FACET facility and operates as an Office of Science National User Facility. FACET-II will provide beams optimized for the next generation of Plasma Wakefield Accelerator (PWFA) experiments and will be the only facility in the world capable of providing 10 GeV electron beams in support of accelerator science R&D. It allocates roughly half of the beam time towards investigating plasma wakefield acceleration in support of the R&D roadmaps defined in the DOE Advanced Accelerator Development Strategy Report [5]. Primary elements of this program include demonstration of a 10 GeV plasma stage with preserved beam quality, development of ultra-high brightness beams from plasma-based injectors and developing high-intensity X-ray and Gamma-ray sources. The other half is dedicated to a diverse set of research programs enabled by high-energy high-intensity electron beams and their interaction with lasers, plasmas and solids. Novel diagnostics to characterize the extreme beams are being developed combining beam-physics, machine learning and artificial intelligence. Future upgrades to deliver 10 GeV high intensity positron beams and upgrades to the 10 TW experimental laser systems are under development to exploit the full scientific potential of the facility.

## 3.2 Universities

### 3.2.1 The Cornell-BNL ERL Test Accelerator (CBETA)

The Cornell-BNL ERL Test Accelerator (CBETA) consists of a 4-turn SRF Energy Recovery Linac with a permanent magnet Fixed Field Alternating-gradient (FFA) arc at Cornell University.

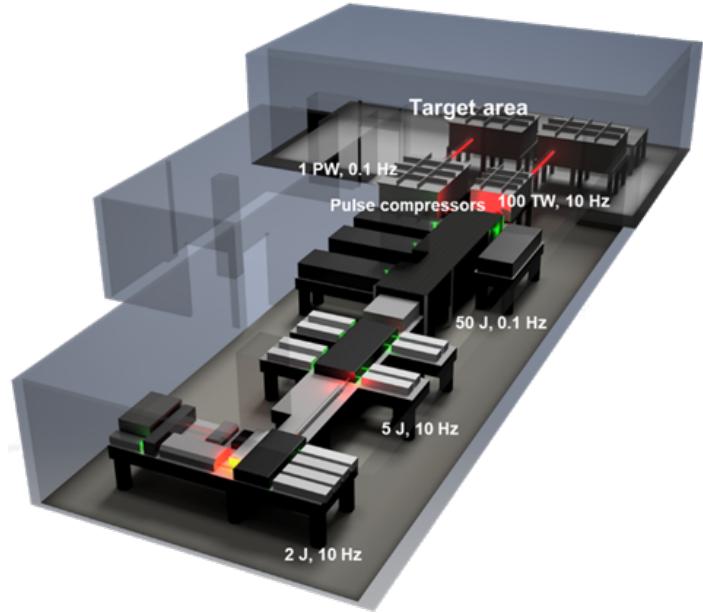


**Figure 5.** Overview of the FACET-II facility. The existing facility includes the photoinjector (electron source), bunch compressors and experimental area (blue) and accelerators in between to achieve the nominal 10 GeV Energy. The facility has been designed to be compatible with upgrades to restore high-energy high-current positron bunches including a refurbished positron target and transfer line, a new compact damping ring and modified bunch compressors (red). The additional compressor upstream of the experimental area will allow simultaneous delivery of electrons and positrons to the experiments.

The facility is equipped for studies of energy recovery, including phenomena such as the beam-breakup instability, beam timing and SRF phasing for simultaneous beam; for permanent magnet technology; and for FFA optics with large energy aperture. An additional focus is the saving of energy in accelerators.

### 3.2.2 Extreme light laboratory, Lincoln, Nebraska

The Extreme Light Laboratory (ELL) is home to the Diocles laser, a petawatt-class laser. It generates light with nearly a million-billion watts of power, or more than 100 times the combined output of all the world's power plants, but compressed into the briefest of bursts. It can recreate some of the most extreme conditions in the universe. Experiments using Diocles enhance the basic understanding of physics and develop solutions for advanced manufacturing, national security and medicine. The lab houses two separate high-intensity femtosecond-duration lasers. One of them, the Diocles Laser, is petawatt class, and has been in operation for over 14 years. It is distinguished by exceptional laser beam quality, stability and parameter control. This enables research with high laser light intensity interacting with either plasmas, or GeV-energy electron beams from a coupled laser-driven wakefield accelerator. The interactions can be studied with synchronized pulses of laser light, electrons or tunable x-rays. A peak laser intensity of  $6 \times 10^{20}$  W/cm<sup>2</sup> was directly measured in an experimental demonstration of high-order multi-photon inverse Compton scattering. The laser and experimental research facility occupies 8,000-sq.-ft. three floors of the Behlen Lab building on the UNL City Campus. The laboratories meet stringent requirements on temperature, humidity, and vibration control, made possible by separate designated electrical, processed-chilled-water, and air-handling systems, and offers flexible experimental arrangements and diagnostics. A total of six large 72"x48"x24" vacuum chambers are available, with three separate and independent beamlines: (1) 0.7-PW peak power at 0.1-Hz repetition rate, (2) 100-TW at 10-Hz and (3) 6-TW at 10-Hz. All use Ti:sapphire chirped-pulse amplification, and lase at 800-nm in 30-fs duration pulses.



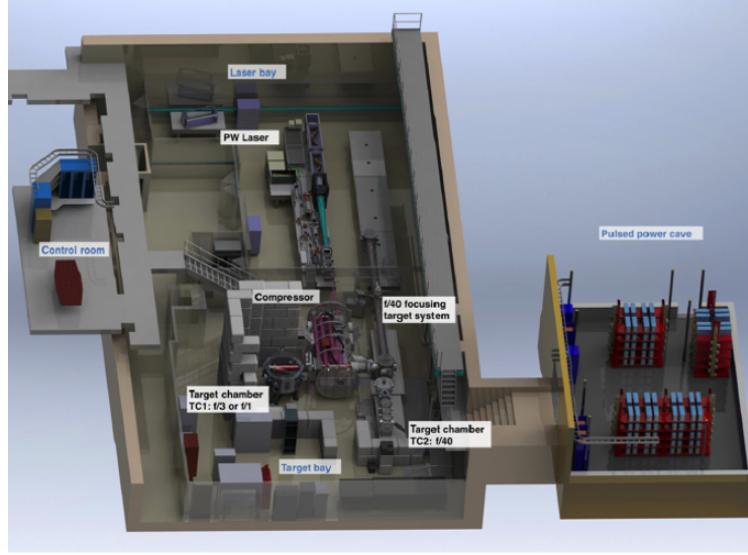
**Figure 6.** The Diocles laser at the Extreme Light Laboratory delivers peak intensity ranging from to  $10^{18} - 10^{21} \text{ W/cm}^2$ .

### 3.2.3 Texas Petawatt Laser, University of Texas at Austin

The Texas Petawatt Laser is a Nd:glass CPA laser using a unique architecture. It combines amplification in a series of Optical Parametric Amplifiers and subsequent high energy amplification in a combination of silicate and phosphate glass to enable recompression of the pulses to under 140 fs, considerably shorter than most glass-based CPA lasers. It can be fired into one of two target chambers, the first (TC1) focuses the beam tightly with an  $f/3$  optic to intensity of well over  $2 \times 10^{21} \text{ W/cm}^2$ . An  $f/1.1$  optic can be deployed in this chamber to yield intensity of over  $10^{22} \text{ W/cm}^2$ . The beam can also be directed into a chamber with a long focal length,  $f/40$  focusing. This is optimal for gas target wakefield acceleration experiments.

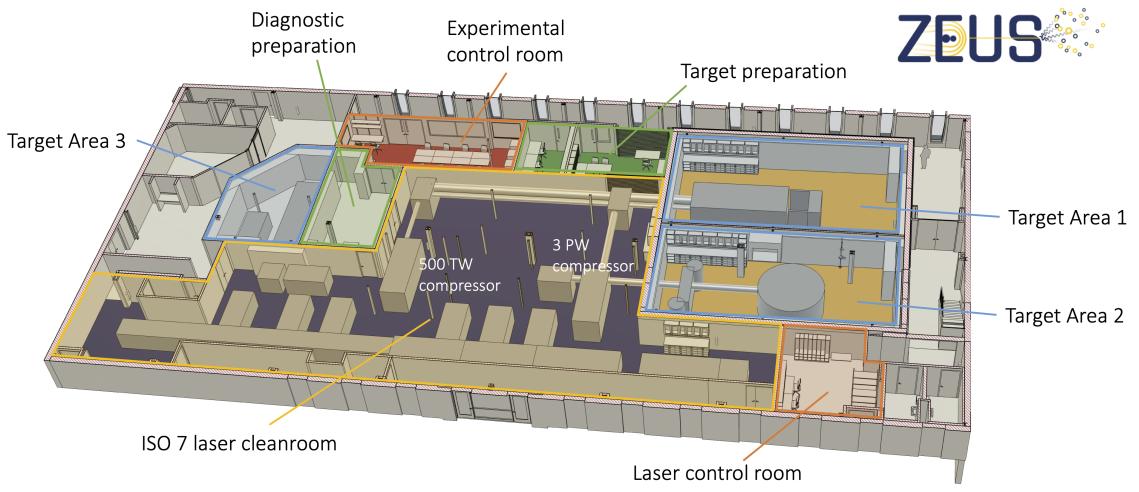
### 3.2.4 ZEUS user facility, University of Michigan

The National Science Foundation (NSF) Zettawatt Equivalent Ultrashort pulse laser System (ZEUS) will be a user facility located at the University of Michigan. Due to become fully operational in late 2023, ZEUS will offer 30 weeks per year to users through a scientific merit based proposal system. There will be several modes of operation into three different target areas, each with different, flexible geometries to support a wide range of experiments. The full 3 PW power (75 J in 25 fs at 800 nm) will be delivered as a single pulse at a repetition rate of 1 shot per minute and should enable focused intensities exceeding  $10^{22} \text{ Wcm}^{-2}$ . Alternatively, the power can be split into one beam with 2.5 PW and the with 500 TW. A signature configuration will use 2.5 PW to drive LWFA to multi-GeV electron energies and the 500 TW pulse will be tightly focused to counterpropagate to the electron beam. The apparent power of the focused laser pulse is boosted proportional to the square of the Lorentz factor (by more than a millionfold) from the Petawatt range to the Zettawatt range. Thus, the wakefield electrons see a Zettawatt Equivalent Ultrashort pulsed laser System – ZEUS. Target



**Figure 7.** Overview of the Texas Petawatt facility.

Area 1 (TA1) will accommodate a very long focal length optic ( $\sim f/60$ ) primarily designed to drive LWFA with up to 3 PW pulses. TA1 will also have a short focal length optic to create high-intensity conditions, that could be counter-propagating to the LWFA electron beam. Target Area 2 (TA2) will have a double plasma mirror capability, to create very high-contrast conditions that are desirable for high-harmonic generation or ion acceleration experiments using solid target interactions. Target Area 3 (TA3) will be operational at 500 TW at have a 5 Hz burst mode with  $f/20$  or  $f/40$  focusing, ideal for many LWFA or secondary betatron x-ray source studies and applications.



**Figure 8.** Overview of the ZEUS facility.

## 4 Research Thrusts

Identifying the most promising accelerator research and development areas to be conducted at the ANA beam test facilities is an ongoing process and subject to continuous revision. For this reason, the US ANA beam test facilities are designed to provide access to a suite of complementary and diverse capabilities to serve a broad community of accelerator scientists drawn from Universities, Industry, and National Laboratories to carry out the national ANA mission.

DOE and NSF work with US accelerator scientists to identify the most promising accelerator research thrusts and these findings have been published a number of documents. In 2016, HEP published the Advanced Accelerator Concepts (AAC) R&D Roadmap [5] for three AAC schemes, laser-driven plasma wakefield acceleration (LWFA), beam-driven plasma wakefield acceleration (PWFA), and structure wakefield acceleration (SWFA). The roadmaps describe a series of near-term, mid-term and long-term research milestones with the final goal of constructing a multi-TeV e+e- collider. Other important research thrusts include the Radiofrequency Accelerator Roadmap [8], Accelerator and Beam Physics Roadmap [9], Accelerator Stewardship [10], Particle Sources, and Artificial Intelligence and Machine Learning [11].

In Table 1, we list the main thrusts of the US ANA program as carried out by the ANA facilities at the national laboratories: advanced acceleration concepts, particle source development, beam physics, and diagnostics and beam control. Note that this list is not exclusive of all accelerator S&T conducted at the US ANA facilities.

## 5 Past Accomplishments

ANA beam test facilities have been instrumental in advancing accelerator S&T throughout their history. These advances can be categorized into primary and secondary goals.

The primary goal of the US DOE GARD program is aimed at supporting the High Energy Physics mission, in particular, the long-term development of advanced accelerator technology towards an energy frontier e+e- linear collider (LC). A few examples of breakthroughs accomplished at the US GARD facilities include: multi-GeV/m accelerating gradients and multi-GeV energy gain in plasma accelerators using beam-drivers at FACET [12] and laser-drivers at BELLA [13], multi-GeV/m positron acceleration at FACET [14], staging of two plasma accelerator modules at BELLA [15], demonstration of controlled injection in a plasma wakefield accelerator [16], record setting transformer ratios at AWA in both structures [17] and plasmas [18], the first demonstration of Optical Stochastic Cooling [19], pioneering work at ATF on shock wave monoenergetic ion acceleration [20], nonlinear effects in inverse Compton scattering (red shift, higher harmonics) [21], high-gain high-harmonic generation FEL [22], fundamental research of electron acceleration in dielectric waveguides (e.g., using 3D woodpile structures [23]), fundamental research on nonlinear Thomson scattering [24], and novel methods for controlled optical injection of electrons into wakefields [25].

In addition to these highlights, in 2016, US DOE published the Advanced Accelerator Roadmap [5] that laid out a series of research plans and goals that would provide the foundation for a technical design report of a multi-TeV linear collider. Significant progress along these

**Table 1.** Research Thrusts of the US National Laboratory ANA Beam Test Facilities.

Research thrust	ATF	AWA	BELLA	FACET-II	FAST
<b>Advanced Acceleration</b>					
LWFA	✓(MeV)		✓(GeV)		
PWFA	✓(MeV)	✓(MeV)		✓(GeV)	
SWFA	✓(MeV)	✓(MeV)		✓(GeV)	
IFEL	✓				
staging	✓	✓	✓		
positron acceleration					✓
<b>Particle Source Development</b>					
plasma-based e- sources		✓	✓	✓	
ion acceleration w/ lasers	✓		✓		
Inverse Compton Scattering	✓		✓	✓	
$\gamma$ ray via filamentation				✓	
coherent X rays from plasmas		✓	✓	✓	
<b>Beam Physics</b>					
phase-space cooling		✓			✓
single $e^-$ & crystalline beams					✓
integrable nonlinear optics					✓
extreme bunch compression					✓
<b>Diagnostics &amp; Beam Control</b>					
novel diagnostics	✓	✓	✓	✓	✓
ML/AI: virtual diagnostics		✓	✓	✓	✓
ML/AI: improve efficiency		✓	✓	✓	
bunch-current shaping	✓	✓	✓	✓	
phase-space/emit. exchange	✓				

roadmaps has been accomplished at the ANA beam test facilities over the last 5 years and they remain critical for pursuing the continued advancements defined in the AAC roadmaps.

A secondary, yet vital goal, is to apply this long-term, general R&D carried out at the ANA facilities to generate spinoff technologies to benefit other applications in science, medicine and industry. Not only does this help validate the accelerator S&T underway but also to benefit other accelerator applications (e.g. light sources, and neutron sources, etc.). Note that these spinoffs often come many years down the road, sometimes decades later. Sometimes they come from Universities, sometimes from National Laboratories, sometimes from Industry, or a combination of two or three stakeholders. A partial list of some of these spinoff technologies is given in Table 2.

## 6 Capabilities

The five US ANA beam test facilities, supported by the DOE Office of Science, HEP General Accelerator R&D (GARD), provide access to a suite of complementary and diverse capabilities, as summarized in Table 3. Similarly, the capabilities of the university-based facilities are summarized

**Table 2.** R&D spinoffs developed and/or demonstrated, at least in part, at US-ANA facilities.

Photoinjector R&D that enabled high brightness sources for X-ray Free Electron Lasers (XFELs)
SASE/FEL R&D demonstrating that the self-amplified spontaneous emission (SASE) instability would work at progressively shorter wavelengths from optical to X-rays
Inverse Free Electron Laser (IFEL) techniques that are basis for the laser heaters used to mitigate instabilities in XFELs
LWFA research that gave rise to betatron X-ray probes at the LCLS Matter in Extreme Conditions (MEC) Instrument
Laser scattering from plasma accelerated beams to generate X-ray and gamma ray probes
Wakefield studies that then were applied to create de-chirpers for XFELs and passive deflectors for UED facilities
Bunch compression studies that informed compressor design for higher peak current and shorter gain length at XFELS
Thomson scattering to measure electron beam emittance and bunch length
Paricle (electron, proton and ion) beams from laser plasma accelerators for probing matter

in Table 4. Capabilities with high-quality beam parameters and diagnostic tools are essential to support research into new beam generation, acceleration, and transport techniques with the potential to mitigate technical risks of upcoming projects and to reduce the cost of future accelerator facilities.

## 7 ANA Beam Test Facility upgrades

In order to continue progress in accelerator science and technology, for instance progress along the AAC Roadmap, major upgrades to the facilities are required.

### 7.1 National Laboratories

#### 7.1.1 ATF

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory. The upgrade plan for ATF facilities reflects the priority set by the science planning workshop [26] based on community input. At the core of this plan is upgrading of the LWIR laser with the goal of delivering reliable CO<sub>2</sub> laser pulses at high repetition rate with a power of > 25 TW and a sub-ps pulse length to the users in the long-term. Such intense LWIR sources (reaching  $a_0$  as high as 8 with  $F_\# \sim 1$  focusing) fill a unique niche in advanced acceleration research for generation of electron and ion beams [27–29]. While the facility is currently capable of producing a 5 TW CO<sub>2</sub> pulse, only about half of that is delivered to users due to limitations of the air transport system. An upgrade to a vacuum transport system as well as the development of nonlinear pulse compression (NLPC) [30] technique is expected to allow the delivery of >10 TW pulses over the next several years with pulse lengths as short as hundreds of femtoseconds. The facility is also pursuing an active R&D program on optical pumping of

**Table 3.** Capabilities: National Laboratory ANA Beam Test Facilities. The “P” label indicates a planned capability.

Capabilities	ATF	AWA	BELLA	FACET-II	FAST
<b>operation model</b>					
National user facility	✓			✓	
Accelerator stewardship	✓			✓	
Collaboration		✓	✓		✓
<b>Beams &amp; Accelerators</b>					
~ 100-MeV $e^-$	✓	✓	✓		✓
~ 10-GeV $e^-$			P		✓
~ 10-GeV $e^+$				P	
high-charge (~ 100 nC) $e^-$ bunches		✓			
proton beams			P		P
NCRF S-band and X-band	✓				
NCRF L-band and X-band		✓		✓	
SCRF L-band and X-band					✓
storage ring					✓
<b>Lasers</b>					
TW-class 800-nm laser (Ti:Sapphire)	✓	✓	✓	✓	
PW-class 800-nm laser (Ti:Sapphire)			✓		
TW-class 10 $\mu$ m laser (CO <sub>2</sub> )		✓			
<b>Plasmas</b>					
plasma capillaries (length [cm])	✓(2)	✓(2)	✓(20)		
gas jets	✓		✓		✓
heat-pipe oven	✓		✓		✓
hollow channel		✓		✓	

CO<sub>2</sub> molecules as well as other technologies that make efficient use of the CO<sub>2</sub> gain profile and enable the delivery of high-repetition rate, high-average power, reliable LWIR pulses. The ATF plans also envision several thrusts for upgrading the linac-driven e-beam, including beam energy and pulse compression. Together with the expanded near IR capabilities, which encompasses the integration and the delivery of a compressed ( $\leq 100$  fs), terawatt-class Ti:Sapphire laser pulse to the IP, simultaneous experiments using the LWIR laser, e-beam, and the Ti:Sapphire enable the research and development of next generation of particle and photon sources.

### 7.1.2 AWA

A proposal to implement a major upgrade of the Argonne Wakefield Accelerator (AWA) to the AWA-HE (HIGH ENERGY) Facility is under development. In several years, after completing the 500-MeV demonstrator, the AWA will become limited in its ability to continue advancing the SWFA Roadmap. Our vision is to continue to advance the Roadmaps by enacting a phased upgrade of the AWA facility so that by the end of the decade the SWFA method will be ready to present an SWFA CDR for a 3-TeV e+e- linear collider. Bunker expansion. Step 1 is to expand the AWA

**Table 4.** Capabilities: University Beam Test Facilities. The “P” label indicates a planned capability.

Capabilities	ELL	Texas	ZEUS
<b>Beams &amp; Accelerators</b>			
~ 100-MeV $e^-$	✓	✓	P
~ 10-GeV $e^-$			P
proton beams	✓	✓	P
<b>Lasers</b>			
TW-class 800-nm laser (Ti:Sapphire)	✓		P
PW-class 800-nm laser (Ti:Sapphire)	✓		P
PW-class 1057-nm laser (Nd:glass)		✓	
<b>Plasmas</b>			
plasma capillaries (length [cm])			
gas jets	✓	✓	P
heat-pipe oven			
hollow channel			

bunker length so that it occupies all available space in its current building. Energy upgrade. Step 2 is to add more RF stations and accelerating structures to increase the energy from 65 to 150 MeV. This will enable GV/m class acceleration gradients and a 3-GeV demonstrator.

### 7.1.3 BELLA

Upgrades are underway to the BELLA PW laser beamline (operating at 1 Hz) to allow the delivery of two synchronized pulses on target, enabling staging at the few GeV level, and a short focal length capability, enabling experiments at ultrahigh intensity (e.g., laser ion acceleration). The BELLA Center is also pursuing a new facility, kBELLA, consisting of a 1 kHz, few J, 30 fs, high average power laser for the demonstration of a high rep-rate, precision LPA and subsequent applications. This will function as a user facility with the kHz, GeV class electron beams and the intrinsically synchronized photon pulses being available for a wide variety of experiments in the basic and applied sciences. One possible candidate laser technology for kBELLA is coherent combining of fiber lasers, which holds promise for providing high average power at high efficiency. To this end, the BELLA Center has a very active R&D program on coherent combining (in both time and space, as well as spectrally) of fiber lasers in collaboration with University of Michigan and LLNL. Furthermore, fiber lasers have the potential to provide high average power and high efficiency at 10 kHz and beyond, which is needed for a future LPA-based collider. The development of high-average power, high efficiency lasers is delineated as an important R&D topic on the Advanced Accelerator Roadmap.

### 7.1.4 FAST

In the coming years, the IOTA ring will be upgraded with a proton injector and an electron lens/cooler [31]. The research with protons and electrons will focus on nonlinear beam optics studies [32], investigation of space-charge effects [33], realization of Electron Lens with its broad

research program [31], continuation of the OSC program [34], and photon science opportunities [35]. A significant required upgrade to the FAST facility is the addition of a laser system to enable research into electron-based coherent radiation generation and activities synergistic with advanced acceleration technologies.

### 7.1.5 FACET-II

As part of the current Snowmass process, the High Energy Physics community is evaluating a e-e+ collider options for precision measurements of the Higgs Boson. Advanced Accelerator technologies are being considered for the possibility of extending the energy reach of such a facility through high-gradient advanced accelerator-based energy boosters or afterburners. Additional studies are looking at the opportunities for Advanced Accelerator technologies to provide an order of magnitude increase in energy for discovery-oriented colliders in the future. In both of these scenarios it is critical to demonstrate a technique for accelerating high-intensity low-emittance positron bunches in plasma. The only experimental studies of positron acceleration in plasma have taken place at SLAC in the Final Focus Test Beam facility (FFTB) and FACET facilities. Novel ideas for positron acceleration using tailored beam drivers and/or plasma sources have been proposed using beam parameters envisioned for FACET-II. A plan is currently being developed to restore positron capabilities to FACET-II and, for the first time, provide the capability to deliver electrons and positrons to the experimental area simultaneously to enable studies of positron acceleration in electron beam driven wakefields.

## 7.2 Universities

### 7.2.1 ELL-Nebraska

The lab now plays a key role in the nation's high-intensity laser research. With renewed funding from the U.S. Department of Energy, the consortium to which it belongs is expanding. DOE established LaserNetUS [7] in 2018. Its 18 million dollar funding boost in 2020, distributed among 10 partner institutions, extends the network for three years. All facilities in LaserNetUS operate high-intensity lasers. Other LaserNetUS host institutions are: Colorado State University, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, SLAC National Laboratory, Ohio State University, Institut National de la Recherche Scientifique, University of Rochester, and University of Texas at Austin. The network and future upgrades to LaserNetUS facilities will provide new opportunities for U.S. and international scientists in discovery science and in technology development. Already, over 200 user scientists and over 100 students and post-docs have utilized the network for their research. This includes research groups hosted by Nebraska from the Air Force Research Laboratory, Brigham Young University, University of Nevada-Reno, and Stanford University.

### 7.2.2 Texas

The Texas Petawatt is evaluating the prospect of undergoing a major rebuild and upgrade in the 2022 to 2024 time scale. The goal will be to build out a 4x beamline facility which will operate with liquid cooled glass amplifiers that can fire at up to one shot per minute (the current laser fires at one shot/hour). This laser will have the option of operating each of the four beams either in

sub-picosecond CPA mode at 1 kJ energy or in long pulse (many ns) mode with up to 3 kJ at the second harmonic (527 nm).

### 7.2.3 ZEUS

ZEUS is supported by the NSF to operate as a user facility, offering 30 weeks of access per year with access being awarded on scientific merit. The range of experimental topics is expected to be broad, ranging from high-field science, to particle acceleration and light source studies and applications, to laboratory astrophysics, to high-energy-density physics probing. It is anticipated the facility will develop its capabilities and diagnostics in response to user needs.

## Acknowledgments

We acknowledge support by the U.S. Department of Energy, Office of Science under contracts DE-AC02-06CH11357 with Argonne National Laboratory, DE-AC02-05CH11231 with Lawrence Berkeley National Laboratory, DE-AC02-07CH11359 with Fermi Research Alliance, DE-SC0018656 with Northern Illinois University, and DE-AC02-76SF00515 with SLAC National Accelerator Laboratory. The ZEUS facility is supported by the University of Michigan, by the National Science Foundation (NSF) through grants PHY-1935950 and PHY-2126181 and by the Air Force Office of Science Research (AFOSR) through grant number FA9550-21-1-0264. The ELL facility is supported by the U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences, under Award No. DE-SC0021018: Laser-NetUS initiative at the Extreme Light Laboratory. Additional support is provided by the U.S. Department of Energy, Office of Science, High-Energy Physics (HEP), under Award No. DE-SC0019421.

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