The ATF Scientific Needs Workshop

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70 YEARS OF DISCOVERY

A CENTURY OF SERVICE

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

These slides are largely based on the Workshop close-out slides (plus some material from the report)

- Summary statements about the workshop
- Summary of each panel's conclusions (technical challenges and Priority Research Directions (PRDs))
  - Topics in Mid-IR Laser Research
  - Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration
  - Topics in Laser-Electron Beam Interactions
- *Workshop/report functionally same as a DOE/SC Basic Research Needs (BRN) workshop/report*

The PRDs we identified were not surprising

- Mid-IR Research
  - High-power CO2/Mid-IR laser development
  - Laser filamentation and atmosphere propagation
  - Secondary sources/CO2 versatility due to nonlinear optics
- LPA Research
  - Electron acceleration
  - Ion acceleration
- 10-TW Laser and E-beam Research
  - Inverse Compton Scattering
  - IFEL
  - Dielectric Laser Acceleration
  - Precision e-beam phase space manipulation (fsec scale)

Committee Charge

1. Conduct an assessment of scientific needs associated with mid-IR Laser capabilities in the 3 targeted areas (*Topics in Mid-IR Laser Research; Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration; Topics in Laser-Electron Beam Interactions*)

2. Evaluate the suitability of the proposed ATF-II Laser System to support the community's needs for mid-IR Laser capabilities

Committee Working Groups

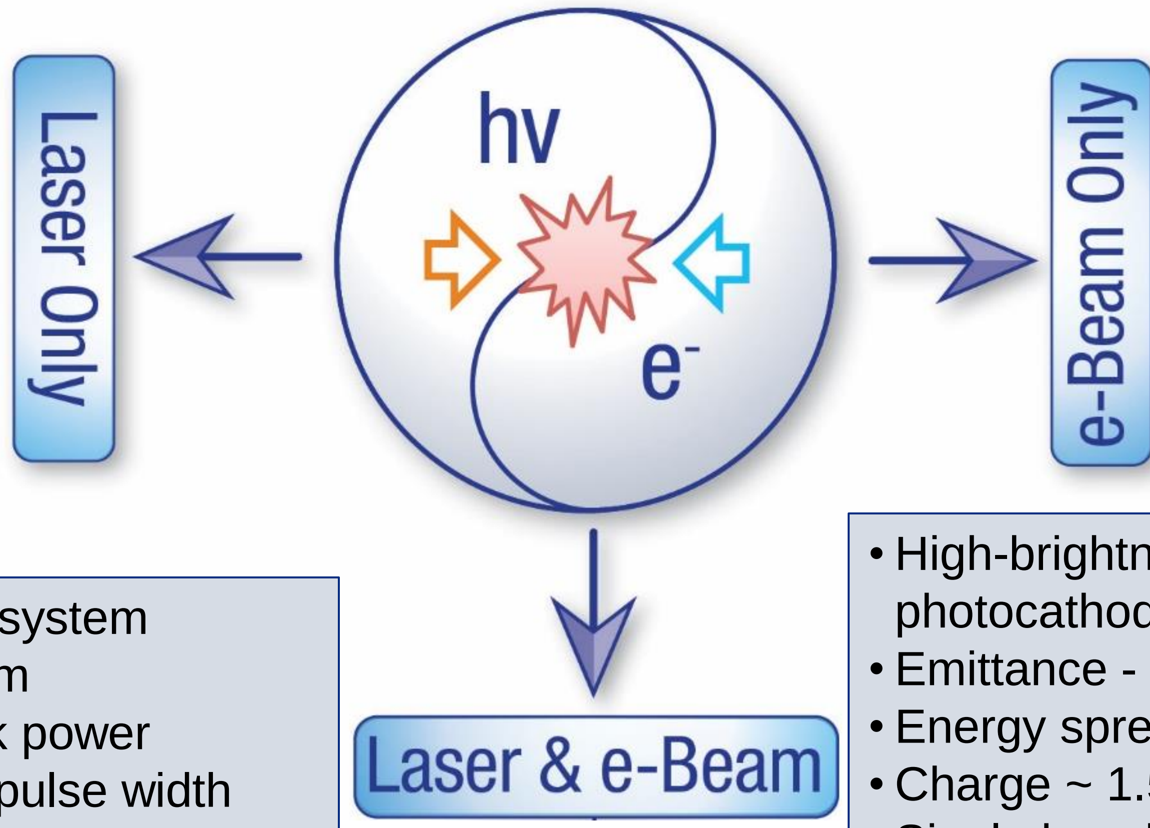
1. Topics in Mid-IR Laser Research
   - Jeff Moses (CU)
   - Dan Gordon (NRL)
   - Yu-hsin Chen (NRL)
2. Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration
   - Stuart Mangles (ICL)
   - Jean-Pierre Delahaye (CERN)
   - Navid Vafaei Najafabadi (SUNY-SB)
   - Aakash Sahai (ICL)
3. Topics in Laser-Electron Beam Interactions
   - Felicie Albert (LLNL)
   - Bruce Carlsten (LANL) (also Committee Chair)
   - Gerard Andonian (Radiabeam/UCLA)

The Committee Strongly Supports the ATF Mission

- ATF plays a central role in advanced accelerator research and development especially for university and smaller-scale R&D
- ATF also plays a leading role in high-power laser technology development
- Evolving to support the broader DOE/SC/HEP/Stewardship portfolio including supporting materials science research*

ATF2 upgrade: DOE turns to the community for advice on upgrades

ATF Provides Unique Electron Beam + Laser Capabilities



- CO_2 laser system
- λ = 9-11 μm
- 2 TW peak power
- 6J @ 3ps pulse width
- 0.05 Hz repetition rate

- High-brightness photocathode linac: 80 MeV
- Emittance - 1μm
- Energy spread - 0.1%
- Charge ~ 1.5 nC
- Single bunch 10 ps – 200 fs
- Multi-bunch trains

WG1 *Topics in Long-Wavelength (Mid-IR) Laser Research*

Current research status

In terms of laser light sources for HEP,

- The U.S. is lagging other countries in infrastructure for high peak power (e.g., ELI-NP, projected to 20 PW in near-IR; Korea has 4 PW laser)
- The U.S. has remained the leader in high power mid-IR facilities (CO_2, BNL and UCLA)

More broadly, laser science and NLO has been driven almost entirely by the Ti:Sapphire laser

- A huge knowledge base (and commercial products) exists for expanding Ti:sapphire capabilities (supercontinuum generation, frequency conversion, EUV generation, THz generation)

WG1 *Topics in Long-Wavelength (Mid-IR) Laser Research*

Future research directions

Future high power CO_2 development led by BNL, UCLA, NRL/AFRL

Alternative high intensity mid-IR source technologies are under development, mainly driven by AMO/NLO community

- OPCPA driven by 1-micron/2-micron amplifiers
- Significant mid-IR NLO materials research (e.g., BAE systems) and gain media development (e.g., Fe:ZnSe @ 4μm)

WG1 *Topics in Long-Wavelength (Mid-IR) Laser Research*

ATF/ATF2 Priority Research Direction 1:

High-power CO2/mid-IR laser development

Technology challenges: Generally speaking, how do we handle the future needs of CO2/mid-IR lasers at higher powers?

Research thrusts:

A. >100 TW operation

B. Sub-ps duration

C. Optics requirements (including damage properties of solids, polarization control, CPA elements, B-integral mitigation…)

D. Shot-to-shot stability, beam quality

E. Synchronization w/ peripheral beams (for ionization control, diagnostics, etc.)

F. Pulse shaping

For example, high pressure discharge technology; efficiency (e.g., energy extraction); isotopic mixtures (reduction of operation costs via recycling, etc.); plasma optics (e.g., for beam/pulse cleaning)

WG1 *Topics in Long-Wavelength (Mid-IR) Laser Research*

ATF/ATF2 Priority Research Direction 2:

Laser Filamentation and Propagation in Atmosphere

Technology challenges: Need $P>P_{cr}$ at minimum (unique to CO_2), whereas $P>>P_{cr}$ provides greater opportunity. Excellent beam quality. Sub-ps durations to address predicted spatiotemporal effects.

Research thrusts:

A. Observation of self-guiding

B. Characterization of plasma

C. Measurements of NL properties of air in LWIR

D. Femtosecond pulse dynamics

WG1 *Topics in Long-Wavelength (Mid-IR) Laser Research*

ATF/ATF2 Priority Research Direction 3:

Secondary sources and expansion of CO2 versatility based on NLO

Technology challenges: ATF facility users require peripheral beams (e.g., for independent control of ionization, diagnostics). Users often have mid-IR needs beyond 10.3 μm. Meanwhile, the NLO community has limited resources for basic research in the LWIR.

Research thrusts:

A. Secondary source generation (e.g., EUV/soft X-ray generation via HHG; THz generation via four wave mixing in gases).
   - This topic overlaps with scientific aims of the AMO physics community exploring ultrafast strong-field light-matter interactions in gases, i.e., non-relativistic laser plasmas, including the physics of strong-field ionization and collisions (HHG, LIED, strong-field processes with $\lambda_{laser} \sim \lambda_{vib}$, etc.)

B. Basic NLO properties of materials in LWIR range

C. Frequency conversion via, e.g., harmonic generation, Raman shifting, DFG/SFG

D. Spectral broadening/continuum generation/nonlinear pulse compression

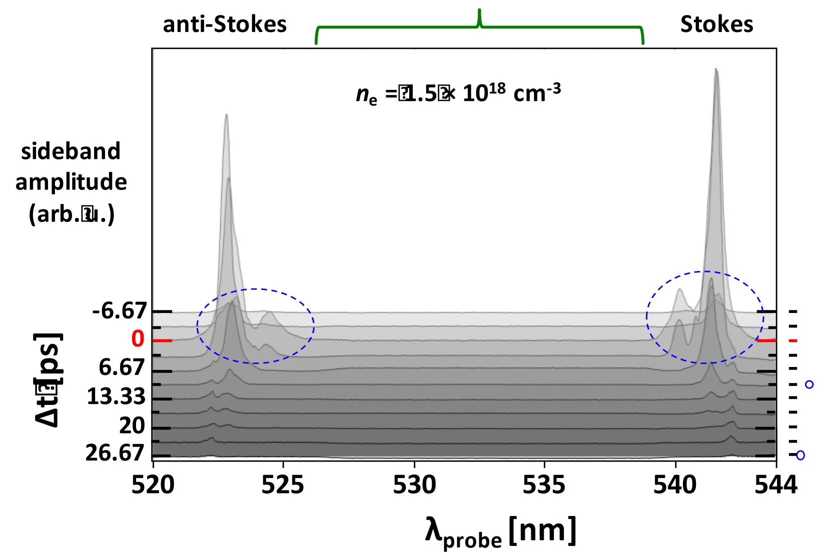
Our thinking: **If you get the NLO community wanting to use ATF for NLO/secondary source development, they will provide R&D for future technologies beneficial to accelerator science at ATF**

WG2 *Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration*

Current research status (Electron Acceleration)

AT ATF:

- First demonstration of Self Modulated Wakefield production with CO_2 laser.



Worldwide:

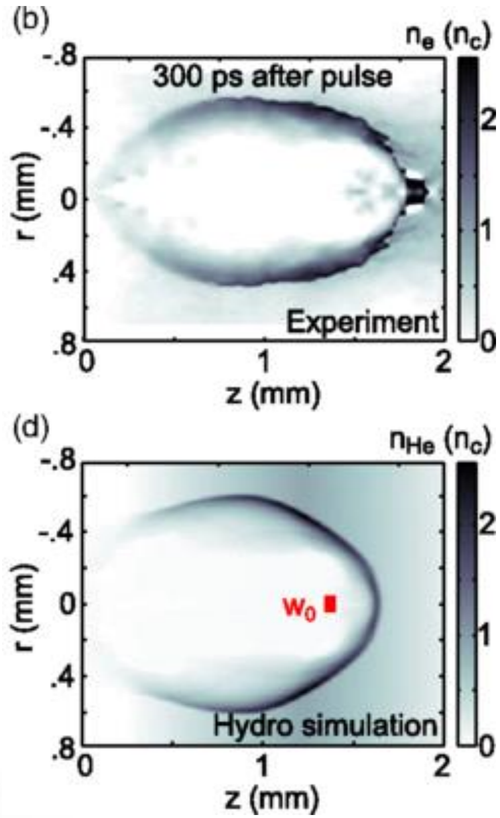
- Multi-GeV LWFA in the blowout regime
- Study of laser particle coupling in ion channel (DLA)
- High brightness e-beam generation through specialized techniques
- Bright X-ray generation and applications
- New directions in mid-IR (MURI programs in US / UK)

WG2 *Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration*

Current research status (Ion Acceleration)

AT ATF:

- Acceleration to ~ 1 MeV in hydro-dynamically shaped gas jets (shock acceleration / hole boring RPA)
- Initial studies on advanced acceleration schemes (MVEA, RITA)



Worldwide:

- Incoherent acceleration
  - TNSA/BOA > 40 MeV
  - Shockwave acceleration – quasi-mono-energetic 20MeV protons
- Coherent Acceleration
  - RPA of ultra thin foils – MeV protons

WG2 *Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration*

Future research directions (Electron Acceleration)

- Advanced injection techniques to produce high brightness e-beam generation through specialized techniques
- External injection and staging: towards an LWFA collider
- Generation of bright X-rays for applications: Medical imaging, probing high energy density science experiments

WG2 *Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration*

Future research directions (Ion Acceleration)

- Quasi mono-energetic 10-20 MeV proton (10TW)
  - proton radiography – security and lithography
  - begin examination of therapeutic effectiveness
- Neutron production – using accelerated beam / target interactions
  - explore applications of CO_2 laser-driven neutron source
- Quasi Mono-energetic >100 MeV ions (25TW)
  - establish therapeutic effectiveness

WG2 *Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration*

ATF/ATF2 Priority Research Direction 1: Laser Wakefield Electron Acceleration

Technology challenges:

High-power, short-pulse CO_2 driver (> 10 TW, < 1 ps).
Synchronized beams (lasers and/or electron beam)

Research thrusts:

A. Accessing highly non-linear wakefield regime: production of self-injected electrons beams; probing of large wake structure

B. High quality electron beams from large bubbles: two color ionization injection; external injection of high-quality electron bunches from linacs

WG2 *Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration*

ATF/ATF2 Priority Research Direction 2: Laser Driven Ion Acceleration

Technology challenges:

High-power, CO_2 driver (> 10 TW); circularly polarized light; pulse shaping/control pre-pulse

Research thrusts:

A. Extending hole-boring ion acceleration to higher energy (10-20 MeV with 10 TW, 100 MeV with > 25 TW)

B. Investigate applications of ion beams: theraputic effectiveness, proton radiography, security and lithography

C. Explore new ion acceleration schemes: e.g. RITA / MVEA

WG3 *Topics in laser-electron beam interaction*

Current research status

- Inverse Compton Scattering
- IFEL electron acceleration
- Electron acceleration in structures
- Electron beam phase space manipulation

WG3 *Topics in laser-electron beam interaction*

Future research directions

High gradient (GeV/m), high efficiency IFEL

High gradient DLA acceleration

Applications of ICS (lithography, nuclear physics, medical)

Sub fsec electron beams

WG3 *Topics in laser-electron beam interaction*

Capabilities of other facilities with laser and e- beam

Facility	Accelerator	E beam (MeV)	Laser	Laser power (W)	Application	Year operation
FACET II*	S band linac	10000	Ti:Sapphire	10^{12} (50 fs)	High gradient e- acceleration	2019-
HIGS*	Storage ring	1200	FEL		ICS, N. Phys	1996-
PLEIADES	S band linac	55	Ti:Sapphire	10^{12} (55 fs)	ICS	2000-2004
T-REX	S band linac	120	Nd:Yag	10^{10} (20 ps)	ICS, N. Phys	2005-2008
Compton	X band linac	30	Ti:Sapphire		ICS	2015-
NewSUBARU	Storage ring	1000	Nd: YVO4	5 (CW)	ICS	2003-
THOMX	Storage ring	70	Fiber		ICS	
PHOENIX	Superc. linac	22.5	Ti:Sapphire		ICS	2013-
ELI-NP*	S/C band linac	19500	Ti:Sapphire	10^{11} (1.5 ps)	ICS, N. Phys	

* Includes user program

WG3 *Topics in laser-electron beam interaction*

ATF/ATF2 Priority Research Direction 1: ICS

Technology challenges: Multiple laser photon energies (1 and 10 µm) at electron/laser interaction point; CO_2 laser recirculation for higher photon flux/conversion efficiency; CO_2 laser polarization

Research thrusts:

A. 100 keV and above nonlinear ICS source for medical and nuclear physics applications

B. EUV ICS source for lithography

WG3 *Topics in laser-electron beam interaction*

ATF/ATF2 Priority Research Direction 2: IFEL

Technology challenges: Undulator technology (tapering) limits high electron energies achieved with 10µm wavelengths; recirculation of laser photons to increase IFEL flux; high power/short pulse CO_2 laser needed to increase acceleration gradients; high efficiency bunch capture.

Research thrusts:

A. Recirculated IFEL

B. 250 MeV IFEL using 2 TW laser upgrade (high power laser enables high gradients)

C. Waveguide IFEL to compensate for diffraction limit, enabled by short pulse CO_2 laser pulses

D. Demonstrate light sources based on IFEL (ICS and soft x-ray FEL)

WG3 *Topics in laser-electron beam interaction*

ATF/ATF2 Priority Research Direction 3: Dielectric Laser Acceleration

Technology challenges: Small beam aperture (scales with laser wavelength – CO2 laser allows larger bunch charge with lower interception); staging (tolerances simplify with longer laser wavelength); high efficiency

Research thrusts:

A. Injection with external prebunched beam (using IFEL to prebunch the beam)
B. Staging multiple acceleration sections
C. Demonstrating high efficiency
D. Demonstrating low interception

WG3 *Topics in laser-electron beam interaction*

ATF/ATF2 Priority Research Direction 4: Precision e-beam phase space manipulation on fs scale

Technology challenges: Laser-electron beam interactions in undulator fields (scales with laser power); delivery of higher order laser modes synchronized to high-quality e-beams

Research thrusts:

A. Sub-fs modulation of electron beam

B. Microbunching on laser wavelength scale for optimum capture in advanced accelerators (e.g. IFEL)

C. Applications to e-beam diagnostics (optical scale deflector, e.g. attoscope, optical circular deflector)

Transformative Research Capabilities

Enabling the ATF2 PRDs

- 10-100 TW, sub-psec mid-IR laser power
- Co-located and synchronized electron, CO2 laser, and NIR beams
- Ability to perform multiple experiments at the same time

Comments on Second Charge Question

Evaluate the suitability of the proposed ATF-II Laser System to support the community's needs for mid-IR Laser capabilities

Near- to Mid-Term Laser Requirements by Topical Area

Experiment	Requirement	ATF-II Laser System
Nonlinear Kerr	1-10 TW	Yes
Non-linear LPA	~2 TW	Yes
Blow-out LPA	5-10 TW, 0.5 psec	Yes
Bubble LPA	25-30 TW, 0.5 psec	Yes
Ion acceleration	25-100 TW, long-term circ. polar.	Yes (power); No* (circ. polar.)
IFEL	25-100 TW	Yes
DLA	10-100 GW, lin. polar.	Yes
ICS	2-10 TW	Yes
ICS OAM	Circ. polar.	No*
Phase space manipulation	~ TW	Yes

* circularly polarized laser light is not currently part of the funded program plan

Near- to Mid-Term Desired Laser Parameter from Survey

Parameter	Requirement	ATF-II Laser System
Power	1-100 TW	Yes (>20 TW is longer term development direction)
Energy	1-100 J	Yes (up to 70 J)
Pulse length	3 psec down to <500 fsec	Yes (<1 psec is longer term development direction)
Stability	< 10% (1%)	Possible. ATF laser system currently tens of % (rms); ATF-II laser system should show significant improvements
Pulse number	Single pulse	Yes
Temporal profile	Pulse shaping	Possible. Some interest in control of pulse shaping
Spatial profile	$M^2 < 1.2$	Good at lower power; transverse shaping responsibility of user
Rep rate	0.1 – 10 Hz	Current design is <0.1 Hz at full power, up to 3 Hz at lower power
Polarization	Circ., lin.	Current design only circular polarization at lower power

Notes and Comments

- Functionally this Scientific Needs Review appears equivalent to a “mission need” review for the ATF2 laser upgrade
- BELLA is HEP’s flagship LPA facility but BELLA can not do much of the research possible on ATF/ATF2 (the ATF capability is unique)
- Important to migrate the e-beam to 912. E-beam/laser experiments have unique value to the community and e-beam only experiments (which are out of this review’s scope) are also important (other DOE e-beam capabilities won’t satisfy all future needs)
- The ATF e-beam outage should be staged after FACET2 has been commissioned

Notes and Comments

- We acknowledge facility pressure from insufficient funding
  - Operations need ~ 11 FTEs
  - Less operating hours due to funding cuts would be unfortunate as the ATF is already heavily oversubscribed – should consider doing two shifts/day like FAST/IOTA
  - Cost split/impact on ATF2 upgrade was not looked at
- We acknowledge pressure from UED/UEM (focus is materials science, not accelerator science so it was not considered by the committee); BES funding possible?
- Full laser e-beam system for e-beam experiments is not likely to replace an RF-based high-quality e-beam system in the near- or mid-term

Summary

Charge 1

Our preliminary assessment of the scientific needs in the three targeted areas identified 10 high priority research directions that the ATF-II is uniquely suited for.

Charge 2

Overall, the proposed ATF-II laser system meets the majority of the community's needs for a mid-IR laser capability.

The PRDs now need further definition with details

- Mid-IR Research
  - High-power CO2/Mid-IR laser development
  - Laser filamentation and atmosphere propagation
  - Secondary sources/CO2 versatility due to nonlinear optics
- LPA Research
  - Electron acceleration
  - Ion acceleration
- 10-TW Laser and E-beam Research
  - Inverse Compton Scattering
  - IFEL
  - Dielectric Laser Acceleration
  - Precision e-beam phase space manipulation (fsec scale)