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

- CO₂ laser system
- \( \lambda = 9-11 \, \mu \text{m} \)
- 2 TW peak power
- 6J @ 3ps pulse width
- 0.05 Hz repetition rate

- High-brightness photocathode linac: 80 MeV
- Emittance - 1\( \mu \)m
- Energy spread - 0.1%
- Charge ~ 1.5 nC
- Single bunch 10 ps – 200 fs
- Multi-bunch trains
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 (CO₂, 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 $\lambda_{\text{laser}} \sim \lambda_{\text{vib}}$, 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.
Current research status (Electron Acceleration)

AT ATF:

- First demonstration of Self Modulated Wakefield production with CO₂ 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
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 CO₂ 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\textsubscript{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: therapeutic effectiveness, proton radiography, security and lithography
C. Explore new ion acceleration schemes: e.g. RITA / MVEA
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

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

* 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

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

* circularly polarized laser light is not currently part of the funded program plan.
### Near- to Mid-Term Desired Laser Parameter from Survey

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>ATF-II Laser System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>1-100 TW</td>
<td>Yes (&gt;20 TW is longer term development direction)</td>
</tr>
<tr>
<td>Energy</td>
<td>1-100 J</td>
<td>Yes (up to 70 J)</td>
</tr>
<tr>
<td>Pulse length</td>
<td>3 psec down to &lt;500 fsec</td>
<td>Yes (&lt;1 psec is longer term development direction)</td>
</tr>
<tr>
<td>Stability</td>
<td>&lt; 10% (1%)</td>
<td>Possible. ATF laser system currently tens of % (rms); ATF-II laser system should show significant improvements</td>
</tr>
<tr>
<td>Pulse number</td>
<td>Single pulse</td>
<td>Yes</td>
</tr>
<tr>
<td>Temporal profile</td>
<td>Pulse shaping</td>
<td>Possible. Some interest in control of pulse shaping</td>
</tr>
<tr>
<td>Spatial profile</td>
<td>( M^2 &lt; 1.2 )</td>
<td>Good at lower power; transverse shaping responsibility of user</td>
</tr>
<tr>
<td>Rep rate</td>
<td>0.1 – 10 Hz</td>
<td>Current design is &lt;0.1 Hz at full power, up to 3 Hz at lower power</td>
</tr>
<tr>
<td>Polarization</td>
<td>Circ., lin.</td>
<td>Current design only circular polarization at lower power</td>
</tr>
</tbody>
</table>
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
  o Operations need ~ 11 FTEs
  o 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
  o 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)