Present status of ATF LASERS
(\textit{CO}_2 \& \textit{YAG})

Marcus Babzien
# ATF laser personnel

<table>
<thead>
<tr>
<th>Name</th>
<th>Responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Igor Pogorelsky</td>
<td>$\text{CO}_2$ “owner”/operator</td>
</tr>
<tr>
<td>Igor Pavlishin</td>
<td>operator, discharge technology</td>
</tr>
<tr>
<td>Marcus Babzien</td>
<td>YAG “owner”/operator</td>
</tr>
<tr>
<td>Daniil Stoliarov</td>
<td>short-pulse upgrades</td>
</tr>
<tr>
<td>Karl Kusche</td>
<td>laser safety, computer controls, data communication</td>
</tr>
<tr>
<td>Donald Davis</td>
<td>mechanical support</td>
</tr>
<tr>
<td>Mikhail Poliansky</td>
<td>LDRD post-doc, new arrival</td>
</tr>
<tr>
<td></td>
<td>+ ATF designers, technicians, electronic engineer, computer engineer</td>
</tr>
</tbody>
</table>
OUTLINE:

Introduction
Principles
What is new since User's Meeting 2005
YAG status – aging gracefully
5-ps 1-TW CO$_2$ regime
  Laser front end
  Pulse measurements
User's experiments
CO$_2$ configuration for micro-bunch experiments
  PASER, Resonance PWA
Intra-cavity pulse train
  ILC LDRD
Synchronized to linac, CO$_2$ and YAG Lasers are principal components of the ATF

YAG: drives RF photocathode slices ps CO$_2$ pulse

CO$_2$: used in laser/e-beam and laser/matter interaction experiments
Facility Layout

- **FEL Room**
- **CO2 Rooms**
- **Experimental Hall**
- **Laser Lab**
- **YAG Room**

- Yellow: Electron Beam
- Red: 10.6 micron CO2
- Orange: 1 micron YAG
- Green: 1/2 micron YAG
- Blue: 1/4 micron YAG

*Brookhaven National Laboratory*

14th ATF Users Meeting, April 4-6, 2007
ATF Nd:YAG Laser Operating Days

535 Total Calendar Days

264 Laser Operating Days, out of 363 “open” days = 73%
## YAG Status - Demonstrated Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy on cathode</td>
<td>0-40 µJ</td>
</tr>
<tr>
<td>Pulse duration (FWHM):</td>
<td>8 ps gaussian</td>
</tr>
<tr>
<td>Range of beam size on cathode (Ø)</td>
<td>0.2 - 3 mm</td>
</tr>
<tr>
<td>Top-Hat Beam Profile Modulation (P-P)</td>
<td>&lt;20%</td>
</tr>
<tr>
<td>Shot-to-shot stability (rms):</td>
<td></td>
</tr>
<tr>
<td>Timing</td>
<td>&lt;0.2 ps</td>
</tr>
<tr>
<td>Energy</td>
<td>&lt;2 %</td>
</tr>
<tr>
<td>Pointing (fraction of beam Ø)</td>
<td>&lt;0.3%</td>
</tr>
<tr>
<td>Drift (8 hour P-P)</td>
<td></td>
</tr>
<tr>
<td>Timing</td>
<td>&lt;1 ps</td>
</tr>
<tr>
<td>Energy</td>
<td>&lt;15 %</td>
</tr>
<tr>
<td>Pointing (fraction of beam Ø)</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>
YAG Upgrades – Beam Profile

Uniformity of electron emission from photocathode affects emittance. Laser uniformity is limited by phase errors in optical elements that are transferred to the intensity domain as the beam propagates to the photocathode.

Some elements such as non-linear crystals and Pockels cells are not easily fabricated to such tight tolerances (<λ/20).

Therefore it is very challenging to passively improve the uniformity of the beam.
A micromirror array as used in commercial projectors is robust enough to serve as an active beam shaper for a laser beam. Mirrors are 13 micron square in a 1024 x 768 matrix. Individually addressable into one of two tilt positions. Array is effectively a grating with electronically variable-blaze. Size of one mirror is below the resolution limit of the transport optics, so groups of mirrors together allow fine control of intensity at every point in beam. Unlike deformable mirrors, works well for low-brightness “tophat” distribution, and incapable of damaging photocathode with tight focus. Already tested with client/server software to characterize beam emittance versus laser modulation.
Old Configuration

From YAG Amp

2x 15 mJ

λ/2

Pockels Cell

2x 10 mJ

To CO2 Slicing

New Configuration

From YAG Amp

5 + 15 mJ

Pockels Cell

1x 5 mJ

Polarizer

1x 15 mJ

To CO2 Slicing
YAG System Replacement: Building an Advanced Drive Laser

The ATF Nd:YAG system has demonstrated excellent performance and is aging well, yet some subsystems are over 20 years old; a replacement is now overdue and we have started development of a purpose-built next generation drive laser.

Better performance than standard off-the-shelf Ti:Sapphire or other laser systems will be achieved by:

➢ Relying exclusively on directly diode-pumped systems instead of more complex, large and failure prone lasers
➢ Choose efficient 1 µm lasing hosts in a mixed gain media configuration to minimize thermal issues and reduce system size
➢ Integrate high-level commercial components in-house to minimize development time while maintaining local expertise
➢ Continue to provide optical synchronization of facility by seeding additional amplifiers for CO2 laser slicing & NIR TW laser
➢ We expect to achieve the following improvements to return ATF to the forefront of photoinjector drive laser performance:

- 100 uJ available UV on cathode (3x more than now)
- Energy jitter 0.2% rms ~ 1% p-p (5x better than now)
- Timing jitter < 200 fs rms (already demonstrated)
- Profile Uniformity ≤ 5% p-p (from desired arbitrary profile) (3x better than now)
- Pointing Jitter ≤ 1% p-p (already demonstrated)
- Temporal shaping (currently limited to gaussian)
- Fast turn-on (already under 15 minutes)
- High Reliability (already provide >1500 hours / year)
- Simple operation (~turn-key) (almost there now!)
Advanced Drive Laser Block Diagram

**Osc.**
- Pulse energy = 1.2 nJ
- Pulse duration = 100 fs
- Peak power = 12 kW
- Repetition rate = 81.6 MHz
- Average power = 100 mW

**Spatial Shaping**
- 100 µJ
- 5 ps
- 20 MW
- 120 Hz
- 12 mW

**Yb:Fiber Pre-Amp**
- 2*0.5 nJ
- 200 ps
- 2.5 W
- 1 kHz
- 1 µW

**Partially Compress**
- 1 mJ
- 5 ps
- 200 MW
- 120 Hz
- 60 mW

**Yb:S-FAP Amp**
- 10 mJ
- 200 ps
- 50 MW
- 120 Hz
- 1.2 W

**Spectral Shaping**
- 50 µJ
- 200 ps
- 250 kW
- 1 kHz
- 40 mW

**Common Photoinjector Configuration**

**Compress**
- 5 mJ
- 500 fs
- 10 GW
- 1 Hz
- 5 mW

**Delay**
- 30 µJ
- 200 ps
- 150 kW
- 1 Hz
- 30 µW

**Vacuum Compressor**
- 300 mJ
- 300 fs
- 1 TW
- 10 Hz
- 3 W

**Yb:Glass Amps**
- 300 mJ
- 300 fs
- 3 GW
- 10 Hz
- 6 W

**ATF–specific Configuration**

**Delay**
- 600 mJ
- 200 ps
- 3 GW
- 10 Hz
- 6 W

**Yb:Fiber Pre-Amp**
- 2*1 µJ
- 200 ps
- 5 kW
- 1 kHz
- 2 mW

**PC chop**
- 2*100 µJ
- 200 ps
- 500 kW
- 1 kHz
- 200 mW

**PC gate**
- 2*80 µJ
- 200 ps
- 400 kW
- 1 kHz
- 160 mW

**PC gate**
- 40 µJ
- 200 ps
- 200 kW
- 1 kHz
- 40 mW

14th ATF Users Meeting, April 4-6, 2007
Advanced Drive Laser Test Stand Schematic

14th ATF Users Meeting, April 4-6, 2007
Investigated gain of different first and second stage fiber amplifiers

Operated at 1 kHz repetition rate

Brought temporal diagnostic into operation and demonstrated short pulse amplification in first fiber stage

Demonstrated gain →

Achieved single pulse energy adequate to start CPOD experiment
# Advanced Drive Laser Original Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Goals</th>
<th>Purchases</th>
<th>Cost (K$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Verify fiber preamp 1 performance up to ~ 1 uJ using ATF oscillator</td>
<td>fiber preamp 1 assembly with pump diodes</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>short pulse diagnostic (FROG or GRENOUILLE)</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>miscellaneous optics and diagnostics</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Prepare oscillator &amp; preamp 1 for optical particle detector experiment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Test fiber preamp 2</td>
<td>multimode fiber</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pump diodes</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>misc optics</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Assemble &amp; test final amplifier using seed from preamp chain</td>
<td>Yb:S-FAP amplifier crystal</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pump diodes</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pockels cells</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>misc optics</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>Construction of final gun driver</td>
<td>new beam transport to gun hutch</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>temporal shaper</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>misc optics</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>216</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
</tr>
</tbody>
</table>
Bandwidth limited amplification of ps CO$_2$ laser pulses

Gain Spectrum

Amplified Picosecond Pulse

Strongly modulated rotational line structure of the CO$_2$ gain spectrum modifies the frequency content of picosecond pulses, changing their temporal structure.

At 10 atmospheres, collisional broadening produces overlap of the rotational lines into the 1 THz wide quasi-continuous gain spectrum, and pulses as short as 1 ps can be amplified without distortion.
High-Pressure CO$_2$ Amplifiers
Principle of Semiconductor Optical Switching

![Graph showing plasma density vs. reflectivity](Image)

- Reflectivity (%)
- Plasma Density (cm$^{-3}$)

$n_{cr}$

Nd:YAG

Initial CO$_2$

Reflected CO$_2$

Transmitted CO$_2$

1 μm plasma layer

Brookhaven National Laboratory

14th ATF Users Meeting, April 4-6, 2007
SH compression in KD*P crystal

Starting with the existing long pulses (14 ps) from the ATF YAG laser, second-harmonic compression can be used to generate ps to sub-ps green pulses.

\[ \frac{\tau_\omega}{\tau_{2\omega}} \sim 3-20 \]

\[ \frac{E_{2\omega}}{E_\omega} \sim 10-80\% \]


SNLO code simulations of 1064 to 532 nm conversion in 10 cm crystal with group velocity mismatch.

- Measured compression from 1 micron to 532 nm with pulse duration decrease of 3-4x in a 10 cm KD*P doubler.
- Energy available at 532 nm is ~ 100 mJ, now limited by input energy.
- New Pockels cell is on order to more efficiently utilize 1 micron energy between gun and CO2 slicing.
- Multi-stage semiconductor slicing using both 1 micron & green pulses will allow few ps CO2 pulse generation for TW operation.

14th ATF Users Meeting, April 4-6, 2007
BNL/ATF CO$_2$ laser System delivers 1 TW, 5 ps pulses

A train of 24-ns spaced pulses is built-up in a regenerative amplifier (upper trace). We switch a single pulse out (bottom trace). However, leakage of preceding pulses defines pre-pulse / pre-plasma conditions on the target.
Regenerative CO$_2$ laser amplifier

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length</td>
<td>15-200 ps 3 ps</td>
</tr>
<tr>
<td>Energy</td>
<td>30 mJ</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Peak power</td>
<td>2 GW       10 GW</td>
</tr>
</tbody>
</table>
Demonstrated and potential CO\textsubscript{2} laser performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length</td>
<td>5-200 ps &lt;1 ps</td>
</tr>
<tr>
<td>Energy</td>
<td>10 J</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>1 / 20 Hz (limited by power supply)</td>
</tr>
<tr>
<td>Peak power</td>
<td>1 TW &gt;5 TW</td>
</tr>
<tr>
<td>Focal spot ((\sigma))</td>
<td>30 (\mu)m 20 (\mu)m</td>
</tr>
<tr>
<td>Laser strength ((a))</td>
<td>0.7 &gt;2</td>
</tr>
</tbody>
</table>
BNL/ATF CO$_2$ laser System delivers 1 TW, 5 ps pulses

The output beam is converted to circular polarized in order to protect the laser system from retro-reflection from the target.
BNL/ATF $CO_2$ laser system delivers
1 TW, 5 ps pulses

3-atm preamplifier

Kerr cell

$CS_2$

Ge switch

5 ps YAG pulse

10-atm regen. amplifier

10-atm final amplifier

14th ATF Users Meeting, April 4-6, 2007
Laser system protection against retroreflection from a target

- **Saturation Absorber**
- **Plasma Shutter**
- **$\frac{\lambda}{4}$**

14th ATF Users Meeting, April 4-6, 2007
Single shot autocorrelator

This folding inverts one beam and thereby causes the beams to intersect in the doubling crystal with opposite transverse time delays.

The transverse time delay is created by using a diffraction grating. The variation in path length across the beam produces a total range of $2\Delta L/c$.
CO$_2$ laser pulse measurements

Microbuncher as a CO$_2$ diagnostic tool

15 ps pulse length is confirmed by time delay scan between the laser and co-propagating 3 ps e-beam while monitoring the IFEL energy modulation.

Autocorrelator measurements

Left - intensity distribution in 10 $\mu$m fundamental beams across the nonlinear crystal with a real time scale.

Right - 2$^{nd}$ harmonic signal corresponding to a single-shot autocorrelation function profile.
CO2 Pulse Sum Frequency Generation Diagnostic

On-line single-shot temporal diagnostic:
- Allows measurement to resolution of streak camera (~2 ps).
- Already shows structure expected from simulations based on known physics of CO2 gain medium
- Awaiting more powerful diode laser for better statistics in streak camera

Picosecond CO2 pulse

808 nm diode laser
AgGaS SFG crystal
850 nm filter
Streak Camera
Characterizing the laser focus

Gaussian approximation

\[ I(r,z) = I_0 \left( \frac{w_0}{w(z)} \right)^2 \exp\left( -\frac{2r^2}{w^2(z)} \right) \]

\[ w_0 = \frac{2}{\pi} \lambda FM^2 \]

\[ 2z_0 = \frac{2\pi w_0^2}{\lambda} \]

\[ F = \frac{f}{D} \]

Realistic beam with \( M^2 = 1.6 \)

Ideal Gaussian beam with the same \( w_0 \).

Ideal Gaussian beam with the same \( z_0 \).

• Laser focus transmitted through pinholes of 75-150 µm dia imaged on IR camera. Gaussian approximation with \( w_0 = 65 \mu m \) is the best fit to the observed transmission through pinholes. For ideal diffraction-limited beam, such focus corresponds to \( F_\# = 10 \) and double Rayleigh distance 2.5 mm. Instead, we measure \( 2z_0 = 0.8 \) mm and \( F_\# = 4 \). This means that the beam has \( M^2 = 1.6 \).

• Conclusions: Laser intensity \( 10^{16} \) W/cm², Target position shall be controlled with 100-200 µm accuracy.

14th ATF Users Meeting, April 4-6, 2007
CO$_2$ laser has been channeled in capillary discharge

This enables a new generation of experiments on laser/e-beam interaction in plasma
Chamber is normally under $10^{-3}$ torr.

Parabolic mirror has fine alignment to control aberrations in the focus which is imaged on IR camera with x40 magnification.

Target position is adjusted with a stepper motor. Transverse target motion allows multiple shots without replacing foil.

Signals on x-ray and optical detectors are recorded without RCF.
Different structure could be the result of systematic change in laser focus position on the target.
IFEL experiment evolved into “Micro-bunch Factory” enabling a new generation of experiments

• Resonance PWFA
• Laser pulse length measurement
• STELLA-IFEL (completed)
• PASER
Micro-bunch "factory" (0.3 Hz)

PASER (in active medium)

Resonance PWA (in capillary plasma)

14th ATF Users Meeting, April 4-6, 2007
Laser test bench at BNL/ATF for advanced feasibility study of intra-cavity Compton source

Purpose of the test:
- Demonstration of 100-pulse train inside regenerative amplifier that incorporates Compton interaction point.
- Demonstration of linear-to-circular polarization inversion inside the laser cavity.
Simplified test setup

Observations:

- Optical gain over 4 μs
- Single seed pulse amplification continues to the end

3% over 1 μs
Near-future CO$_2$ laser plans from 2005 (completed)

- Establish 3-ps TW regime of operation for user’s experiments.
- Improve and expand on-line laser diagnostics. (Includes CO$_2$ autocorrelator modification for short-pulse measurement.)
- Develop techniques for isolating the laser system from parasitic feedback (back reflections) from a target plasma.
- Work on characterizing and controlling the contrast.
- Acquire capability for simulating ps pulse amplification.
- Prepare a proposal for a femto-second upgrade.*
Summarizing Progress Since Last Meeting

- Pulse shortening from 25 ps to 5 ps allowed to achieve 1 TW peak power.
- Focusing to \( w_0 = 65 \mu\text{m} \) size, we achieved \( a_0 = 0.7 \).
- After practical realization of a regime with improved high-contrast and parasitic reflections suppressed, the short-pulse laser is applied to user’s experiments (nonlinear Thomson, ion acceleration, LWFA).
- Laser is configured for quick switching to a higher-repetition-rate, 200 ps pulse regime to support user’s experiments that require microbunching (PASER, resonance PWA).
- New diagnostic and simulation capability allow better characterizing of the laser pulse and support laser development.
- Demonstration of a pulse train inside a picosecond CO\(_2\) laser amplifier supports a new initiative on using intra-cavity gamma source for ILC positron production.
Near-future CO$_2$ laser plans 2007

- Establish 1-ps multi-TW regime of operation for user’s experiments.
- Achieve $a_0=2$ via higher power and tighter focus.
- Improve diagnostics and modeling to apply to new and potential regimes of operation.
- Continue with high-repetition rate laser R&D closer the ILC requirements.
- Prepare proposal for laser facility to prototype ILC Compton source.
- Prepare a proposal for a femto-second upgrade.