Experience with and expectations for the drive laser for the APS PC gun

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* Current APS drive laser
  Configuration, and features
  Problems and solutions
  Current performances, and surprises
  Summary

* Expectation for the next drive laser
  Operation and performance requirement
  Some commercial systems, new ideas
  Adaptive emittance optimization loop
  Summary

* Acknowledgement
Role of the APS pc gun drive laser

LEUTL: the free electron laser project

Saturated at wavelength as short as 150 nm
100-200 fs pulses, energy 60-250 µJ

1 nC
0.5-10 ps
3 mm mrad
200-450 MeV
**APS pc gun drive laser**

**Flash lamp-pumped Nd:Glass**

Chirped pulse amplification laser

- **Imaging aperture**
- **Divergence control**
- **BBO**
- **Spectrometer**
- **Single-shot autocorrelator**
- **Scanning Autocorrelator**

**6 Hz, 0.4 mJ @ 263 nm**

- **1.8 nm bandwidth**
- **1-10 ps pulse duration**
- **Time jitter, 2 ps spec (?)**

Features

Environment Monitoring
  Temperature and humidity

Laser monitoring
  Oscillator
    Energy (off line), pulse duration (off line), mode, spectrum,
  Amplifier
    Cavity buildup, mode, pulse duration, FROG (offline)
  UV
    Energy, mode, virtual cathode

Laser control
  Off line: Pulse duration, divergence, spot size on VC
  On line: Pulse energy, trajectory
  Semi automatic cathode cleaning
FROG traces of the laser

Input trace is 

Raw

Reconstructed

Time domain, FWHM=946 fs

Frequency domain, FWHM=1.514 nm
Semi automatic cathode cleaning

Before

After
## Problems and solutions

<table>
<thead>
<tr>
<th>Problem</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor beam profile</td>
<td>• Replacing KDP with BBO</td>
</tr>
<tr>
<td>mode inhomogenity</td>
<td>• Adding pinholes at both end of the cavity</td>
</tr>
<tr>
<td>higher order mode</td>
<td>• Sealing the transport line</td>
</tr>
<tr>
<td>Poor pointing stability</td>
<td>• Imaging</td>
</tr>
<tr>
<td>50% rms</td>
<td>• Sealing the transport line</td>
</tr>
<tr>
<td>Poor output</td>
<td>• Replacing stretcher-compressor gratings</td>
</tr>
<tr>
<td>up to 50% rms</td>
<td>(From originally unknown 1800 l/mm, 76% efficiency to JY 1740 l/mm, 90% efficiency)</td>
</tr>
<tr>
<td>not enough energy</td>
<td>• Scheduling flash lamp replacement</td>
</tr>
<tr>
<td>Poor reliability</td>
<td>• Switching cathode from Cu to Mg</td>
</tr>
<tr>
<td>mechanical broken rods</td>
<td>• Switching Kigre rods to Schott rods</td>
</tr>
<tr>
<td>optical damage</td>
<td>• Adding pinholes to cavity</td>
</tr>
<tr>
<td>Intense maintenance</td>
<td>• Hiring a baby sitter</td>
</tr>
</tbody>
</table>
IR Spatial Profile

\[ \sigma_x = 1.14 \text{ mm} \]
\[ \sigma_y = 0.79 \text{ mm} \]

30-40 mW @ 6 Hz
Virtual cathode images

Direct beam

Size: variable
Profile: 30% flat top
Pointing stability: ~2%

Hard edge image
Frequency conversion

The power in the second harmonics at matched phase is (with pump depletion)

\[
\frac{P_{2\omega}}{P_\omega} = \tanh^2 \left( \frac{L}{L_{NL}} \right)
\]

\[
L_{NL} = \frac{1}{4\pi d_{eff}} \sqrt{\frac{2\varepsilon_0 n_\omega^2 n_{2\omega} c \lambda_{\omega}^2}{I_\omega}}
\]

For BBO, type I critical phase match

<table>
<thead>
<tr>
<th></th>
<th>( \lambda_\omega ) (( \mu m ))</th>
<th>( n_\omega )</th>
<th>( n_{2\omega} )</th>
<th>( d_{eff} ) (pm/v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHG</td>
<td>1.053</td>
<td>1.6551</td>
<td>1.6551</td>
<td>1.9</td>
</tr>
<tr>
<td>FHG</td>
<td>0.527</td>
<td>1.6749</td>
<td>1.6749</td>
<td>2.0</td>
</tr>
</tbody>
</table>

\[
L_{NL2\omega} = \frac{6913}{(P_\omega / A)^{1/2}}
\]

\[
L_{NLA\omega} = \frac{3443}{(P_\omega / A)^{1/2}}
\]

At low intensity

\[ P_{4\omega} \propto P_\omega^4 \]

At high intensity

\[ P_{4\omega} \propto P_\omega \]
Frequency conversion

Expected Conversion efficiency

<table>
<thead>
<tr>
<th></th>
<th>Green/IR</th>
<th>UV/Green</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old gratings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New gratings</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Measured
- Green/IR: 53%
- UV/green: 20%

<table>
<thead>
<tr>
<th></th>
<th>1.064 μm</th>
<th>0.532 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular acceptance (mrad cm)</td>
<td>0.53</td>
<td>0.16</td>
</tr>
<tr>
<td>Temperature bandwidth (K cm)</td>
<td>51</td>
<td>4.0</td>
</tr>
<tr>
<td>Wavelength bandwidth (nm cm)</td>
<td>2</td>
<td>0.073</td>
</tr>
</tbody>
</table>

UV Energy stability

Lamps at 1 million shots

\[
\begin{align*}
\langle E \rangle &= 9.68 \, \mu J \\
\sigma_{E}/\langle E \rangle &= 1.7% \\
20021012
\end{align*}
\]

\[
\begin{align*}
\text{Counts}
\end{align*}
\]

\[
\begin{align*}
E/\langle E \rangle - 1
\end{align*}
\]

Lamps at 10 million shots

\[
\begin{align*}
\langle E \rangle &= 208 \, \mu J \\
\sigma_{E}/\langle E \rangle &= 4.3% \\
20020927
\end{align*}
\]

\[
\begin{align*}
\text{Counts}
\end{align*}
\]

\[
\begin{align*}
E/\langle E \rangle - 1
\end{align*}
\]
**Surprise: Timing stability**

**Laser oscillator**  TBWP GLX-200 oscillator at 119 MHz

**Lock device**  TBWP CLX-1000 timing stabilizer with spec <2 ps

**RF source**  Gigatronics 2856 MHz/24 or Crystal oscillator 119 MHz

**119 MHz rf waveform**

**Laser rf waveform**

**Laser rising edge**  171 ps p-p, 19 ps rms

**Laser falling edge**  56 ps p-p, 7 ps rms
Summary on current laser

* Finally usable in stability and profile

However: it is stretching its limit ….

* Flash lamps age quickly
  
  10 million shots is the margin we use now
  3-weeks of 24-7 operation at 6 Hz
  Needs careful attention for stable operation at the end

* Laser rods break at about 15 million shots or less
  
  Time consuming
  Changes laser characteristics: divergence, mode size, optical path, etc….

• No room for further improvement
  
  Energy stability, reliability, etc..
Time to dream for a new drive laser
The future APS drive laser

Role

Primary electron beam source for both LEUTL and APS in routine operation (LEUTL is becoming a user facility)

Key operational requirement

Turn key system
Reliable: no break down during normal operation
Stable over long time
Minimum maintenance
Deliver up to 5 nC per shot for injection to APS
# The role of cathodes

<table>
<thead>
<tr>
<th>Cathode</th>
<th>((E_{\text{gap}} + E_A)/\text{eV})</th>
<th>Q.E. ((263\text{nm}))</th>
<th>Life</th>
<th>Laser energy/nC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>4.5-5.6 eV</td>
<td>(2\times10^{-6})</td>
<td>Long</td>
<td>2.4 mJ 160 µJ 120 µJ</td>
</tr>
<tr>
<td></td>
<td>3\times10^{-5}</td>
<td>(3\times10^{-5})</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4\times10^{-5}</td>
<td>((\text{APS}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>((\text{Nguyen, LANL}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>((\text{GTF}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>3.78 eV</td>
<td>(1.3\times10^{-4})</td>
<td>Long</td>
<td>36 µJ 3.6 µJ 1.6 µJ</td>
</tr>
<tr>
<td></td>
<td>(1.3\times10^{-3})</td>
<td>(3\times10^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(3\times10^{-3})</td>
<td>((\text{APS}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>((\text{Nguyen, LANL}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cs₂Te</td>
<td>3.5 eV</td>
<td>5%</td>
<td>Months</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>((\text{Nguyen, LANL}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>((\text{FNAL}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CsI</td>
<td>6.4 eV</td>
<td>Est. (10^{-3})</td>
<td>Long</td>
<td></td>
</tr>
<tr>
<td>K₂CsSb</td>
<td>2.1 eV</td>
<td>10%</td>
<td>Hours</td>
<td></td>
</tr>
<tr>
<td>Cs₃Sb</td>
<td>2.05 eV</td>
<td>6%</td>
<td>Unstable</td>
<td></td>
</tr>
</tbody>
</table>

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### Laser: Dream vs reality

<table>
<thead>
<tr>
<th>Current</th>
<th>Dream</th>
<th>Reality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse energy on cathode&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt;500 µJ</td>
<td>100 µJ</td>
</tr>
<tr>
<td>Pulse repetition rate&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6 Hz</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Energy stability</td>
<td>2% rms</td>
<td>0.5% rms</td>
</tr>
<tr>
<td></td>
<td>5-10% p-p</td>
<td>2% p-p</td>
</tr>
<tr>
<td>Pulse length</td>
<td>2-10 ps</td>
<td>2-10 ps</td>
</tr>
<tr>
<td>Pulse shaping</td>
<td>Possible</td>
<td>Y</td>
</tr>
<tr>
<td>Profile shaping</td>
<td>Semi</td>
<td>Y</td>
</tr>
<tr>
<td>Spatial homogeneity</td>
<td>50%</td>
<td>10%</td>
</tr>
<tr>
<td>Pointing stability</td>
<td>1-5% rms</td>
<td>1% p-p</td>
</tr>
<tr>
<td>Timing jitter to rf</td>
<td>6 ps rms</td>
<td>&lt;0.5 ps</td>
</tr>
<tr>
<td></td>
<td>(2 ps spec)</td>
<td></td>
</tr>
</tbody>
</table>

#### Advanced features

- Active hydrothermal control: N | Y | 😊 |
- Automatic energy control: Possible | Y | 😊 |
- Automatic emittance optimization: N | YYY | 😞 R&D needed |

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<sup>a</sup> Based on APS QE for a Mg cathode of about $1.3 \times 10^{-3}$, for 1 nC of charge from the gun.

<sup>b</sup> With long life cathode, single pulse per rf cycle. For a SC rf with higher duty factor the requirement is different.
### Commercial Ti:Sa amplifier systems

#### Advertised performances

<table>
<thead>
<tr>
<th>Make and model</th>
<th>Rep rate</th>
<th>Energy</th>
<th>Stability</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clark MXR, CPA-2010</td>
<td>0.2-2 kHz</td>
<td>&gt;0.6 mJ</td>
<td>1%</td>
<td>TM00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Built in active hydrothermal Stabilization)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectra Physics, Spitfire</td>
<td>1-5 KHz</td>
<td>0.7 mJ</td>
<td>1% (p-p)</td>
<td>TM00, 1.5 diffraction limit</td>
</tr>
<tr>
<td>Spectra Physics, Hurricane</td>
<td>1-5 KHz</td>
<td>0.7 mJ</td>
<td>1.5% (p-p)</td>
<td>TM00, 1.5 diffraction limit</td>
</tr>
<tr>
<td>Femto Lasers, FemtoPower</td>
<td>1 kHz</td>
<td>0.8 mJ</td>
<td>2% (p-p)</td>
<td>TM00, 2 diffraction limit</td>
</tr>
<tr>
<td>Coherent RegA9000</td>
<td>300 kHz</td>
<td>4 µJ</td>
<td>2% (p-p)</td>
<td>TM00, 2 diffraction limit</td>
</tr>
</tbody>
</table>

#### Performance Example

**Spectra Physics-Positive Light Hurricane**

Energy stability <1.5% p-p, 0.24% rms @ 1k Hz (http://www.poslight.com/)

![Graphs showing performance example](http://www.poslight.com/)
An idea: Gain less amplifier

Seed: high rep, low energy pulses, \( f, E_s \)

Cavity with length matching the rep rate of the seed, \( L = \frac{1}{f} \)

Low rep output

\[
E_{\text{out}} = nE_s = \frac{E_s}{\text{loss}}
\]

Example: 300 mW, 100 MHz, for loss=\(10^{-4}\), \(E_{\text{out}} = 30 \, \mu\text{J} @100 \, \text{kHz}\)

Advantages

Ultra stable: \( E_{\text{out}} = nE_s \)  
Linear device: easier to shape  
Low jitter: no jitter between seed and output

Jones and Ye, Opt Lett 27, 1848 (2002)
### Commercial lockable oscillators

#### Advertised performance

<table>
<thead>
<tr>
<th>Make and model</th>
<th>rep rate</th>
<th>jitter spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBWP TIGER 200/CLX1100</td>
<td>up to 150 MHz</td>
<td>&lt;1 ps</td>
</tr>
<tr>
<td>Femto Laser Femto Source/Femtolock</td>
<td>up to 150 MHz</td>
<td>&lt;1 ps</td>
</tr>
<tr>
<td>Spectra-Physics Lok-to-Clock Tsunami</td>
<td>up to 100 MHz</td>
<td>&lt;1 ps</td>
</tr>
<tr>
<td>Coherent Mir Synchro-Lock</td>
<td>up to 100 MHz</td>
<td>&lt;2 ps</td>
</tr>
</tbody>
</table>

Laser: TBWP TIGER 200 oscillator at 119 MHz  
Locking: TBWP CLX1100  
RF source: HP 8665B at 119 MHz  

**Test results** 8 ps

"Subfemtosecond timing jitter between two independent, actively synchronized, mode locked lasers"  
Adaptive pulse manipulation

Laser

SLM pulse shaper
Deformable mirror

Longitudinal and transverse profile control

Single shot longitudinal profile measurement
Transverse profile measurement

Single shot Emittance measurement

Electron beam
Measurement techniques

Laser longitudinal profile
FROG is the choice
  in IR, green, SHG
  in UV, Polarization gating

**FROG example**

Single-shot emittance measurement
Multi slit mask

---

Summary

Laser

Laser technology is mature enough for the basic requirement

Advanced features

R&D is needed to adapt existing adaptive pulse shaping and waveform control technologies
Acknowledgement

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