Advancements in Laser Technology and Applications to Accelerators

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Applications of laser technology to accelerators

- Laser-based nonintrusive beam diagnostics
- Photoinjectors
- Laser stripping
- Compton scattering based light source
- Laser wakefield plasma acceleration
- Laser driven ion acceleration via thin films
Map of laser specs

Pulse Energy (J)

<table>
<thead>
<tr>
<th>Repetition Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mW</td>
</tr>
<tr>
<td>1 W</td>
</tr>
<tr>
<td>1 KW</td>
</tr>
<tr>
<td>1 MW</td>
</tr>
<tr>
<td>1 GW</td>
</tr>
</tbody>
</table>

10^9 10^6 10^-3 10^3 1 10^-3 10^-6 10^-9
Pulse energy and repetition rate in laser specs

![Diagram showing pulse energy and repetition rate for different laser specifications.](image-url)
Laser based nonintrusive beam diagnostics

- Lasers are commercial off-the-shelf
- Optical engineering effort for operational service
Laser wire beam profile monitor

Laser

X-scan

Y-scan

H⁻ beam

Bending Magnet

H⁰

H⁻

electron

Faraday Cup
Layout of the SNS SCL laser wire system

- 4 LW from 200 MeV
- 4 LW from 450 MeV
- 1 LW at 1 GeV
Laser beam position stabilization with feedback control

\[ y(t) = x(t) + g \varepsilon(t - t_d), \]
\[ \varepsilon(t) = \lambda \varepsilon(t - t_d) + k \delta(t), \]
\[ \delta(t) = Y_T - y(t). \]
1-MW H⁻ profiles measured by laser wire at SCL
# Laser specs for photoinjectors and laser stripping

<table>
<thead>
<tr>
<th></th>
<th>(\lambda) (nm)</th>
<th>Micropulse Length</th>
<th>Micropulse Frequency</th>
<th>Micropulse Energy</th>
<th>Macropulse Length/Rep Rate</th>
<th>Power in Burst</th>
<th>Average Power</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fermilab NICADD Photoinjector</strong></td>
<td>351</td>
<td>5 ps</td>
<td>81.25 MHz</td>
<td>20 uJ</td>
<td>800 us @ 1 Hz</td>
<td>1.6 kW</td>
<td>1.3 W</td>
</tr>
<tr>
<td><strong>TTF Photoinjector</strong></td>
<td>262</td>
<td>10 ps</td>
<td>1 MHz</td>
<td>53 uJ</td>
<td>800 us @ 10 Hz</td>
<td>53 W</td>
<td>0.4 W</td>
</tr>
<tr>
<td><strong>FLASH Photoinjector</strong></td>
<td>800</td>
<td>7 fs</td>
<td>1 MHz</td>
<td>1 mJ</td>
<td>800 us @ 10 Hz</td>
<td>1 KW</td>
<td>8 W</td>
</tr>
<tr>
<td><strong>European XFEL Photoinjector</strong></td>
<td>800</td>
<td>10 fs</td>
<td>4.5 MHz</td>
<td>5 mJ</td>
<td>650 us @ 10 Hz</td>
<td>22 KW</td>
<td>150 W</td>
</tr>
<tr>
<td><strong>NLS Photoinjector</strong></td>
<td>800</td>
<td>30 fs</td>
<td>1 MHz</td>
<td>50 mJ</td>
<td>CW</td>
<td>50 KW</td>
<td></td>
</tr>
<tr>
<td><strong>CEBAF Photoinjector</strong></td>
<td>780</td>
<td>100 ps</td>
<td>499 MHz</td>
<td>4 nJ</td>
<td>CW</td>
<td>2 W</td>
<td></td>
</tr>
<tr>
<td><strong>LCLS Photoinjector</strong></td>
<td>255</td>
<td>10 ps</td>
<td>119 MHz</td>
<td>2.5 mJ</td>
<td>1-40 micropulses @ 120 Hz</td>
<td>300 KW</td>
<td>&lt;12 W</td>
</tr>
<tr>
<td><strong>SNS Laser Stripping (Intermediate Stage)</strong></td>
<td>355</td>
<td>50 ps</td>
<td>402.5 MHz</td>
<td>50 uJ</td>
<td>10 us @ 10 Hz</td>
<td>20 KW</td>
<td>2 W</td>
</tr>
<tr>
<td><strong>SNS Laser Stripping</strong></td>
<td>355</td>
<td>50 ps</td>
<td>402.5 MHz</td>
<td>50 uJ</td>
<td>1 ms @ 60 Hz</td>
<td>20 KW</td>
<td>1.2 KW</td>
</tr>
<tr>
<td><strong>Project X Laser Stripping</strong></td>
<td>1064</td>
<td>81 ps</td>
<td>325 MHz</td>
<td>1.2 mJ</td>
<td>1.25 ms @ 5 Hz</td>
<td>390 KW</td>
<td>2.4 KW</td>
</tr>
</tbody>
</table>
# Laser Specs in ICS Experiments

<table>
<thead>
<tr>
<th>Facility</th>
<th>Laser System</th>
<th>λ (nm)</th>
<th>Pulse Energy/Width</th>
<th>e-beam Energy</th>
<th>X-/γ-ray Energy</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>U. Tokyo</td>
<td>Nd:YAG</td>
<td>532</td>
<td>25mJ / 10ns</td>
<td>45 MeV</td>
<td>10-60 KeV</td>
<td>$10^5$ Hz</td>
</tr>
<tr>
<td>KEK</td>
<td>Nd:YAG</td>
<td>1064</td>
<td>112uJ / 7ps</td>
<td>50 MeV</td>
<td>30 KeV</td>
<td>$10^5$ Hz</td>
</tr>
<tr>
<td>BNL/ATF</td>
<td>CO₂</td>
<td>10,600</td>
<td>2J / 6ps</td>
<td>64-72 MeV</td>
<td>8 KeV</td>
<td>$10^8$ per shot</td>
</tr>
<tr>
<td>AIST/Japan</td>
<td>Ti:Sapphire</td>
<td>800</td>
<td>100mJ / 100fs</td>
<td>40 MeV</td>
<td>20-40 KeV</td>
<td>$10^6$ Hz</td>
</tr>
<tr>
<td>RadiBeam</td>
<td>Nd:YAG</td>
<td>532</td>
<td>620mJ / 10ps</td>
<td>547 MeV</td>
<td>10.8 MeV</td>
<td>$10^{14}$ Hz</td>
</tr>
<tr>
<td>JAEA</td>
<td>Nd:YAG</td>
<td>1064</td>
<td>1.8uJ / 1ps</td>
<td>350 MeV</td>
<td>0.5-9 MeV</td>
<td>$10^{13}$ Hz</td>
</tr>
<tr>
<td>ELSA/France</td>
<td>Nd:YAG</td>
<td>532</td>
<td>200mJ / 30ps</td>
<td>19 MeV</td>
<td>13.6 KeV</td>
<td>$10^8$ per pulse</td>
</tr>
</tbody>
</table>
Pulse energy and repetition rate in applications

- **Pulse Energy (J)**
  - $1\text{ mW}$
  - $1\text{ W}$
  - $1\text{ KW}$
  - $1\text{ MW}$
  - $1\text{ GW}$

- **Repetition Rate (Hz)**
  - $10^{-6}$
  - $10^{-3}$
  - $1$
  - $10^3$
  - $10^6$
  - $10^9$

- **Beam diagnostics**
- LCLS Photoinjector
- FLASH Photoinjector
- γ-ray source (AIST)
- Project X Stripping
- SNS Laser Stripping
- Current LPA/LIA Experiments
- X-ray (U. Tokyo)
- 1 TeV Collider

**Applications**

- **Current LPA/LIA Experiments**
- **X-ray (U. Tokyo)**
- **1 TeV Collider**
- **LCLS Photoinjector**
- **γ-ray source (AIST)**
- **Project X Stripping**
- **SNS Laser Stripping**
- **Beam diagnostics**
## Gap between application requirements and available specs

### Table: Repetition Rate (Hz) vs. Pulsed Energy (J)

<table>
<thead>
<tr>
<th>Repetition Rate (Hz)</th>
<th>Pulse Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Hz</td>
<td>1 mW</td>
</tr>
<tr>
<td>10 Hz</td>
<td>1 W</td>
</tr>
<tr>
<td>10^3 Hz</td>
<td>1 kW</td>
</tr>
<tr>
<td>10^6 Hz</td>
<td>1 MW</td>
</tr>
<tr>
<td>10^9 Hz</td>
<td>1 GW</td>
</tr>
</tbody>
</table>

### Diagram:

- **LLNL PW**: 10 W
- **Vulcan**: 1 kW
- **HERCULES**: 10 kW
- **Gekko**: 100 kW
- **LOA**: 1 MW
- **X-ray (U. Tokyo)**: 1 GW
- **1 TeV Collider**: 10^12 W
- **1 TeV Collider**: 10^13 W
- **Project X Stripping**: 10^14 W
- **LCLS Photoinjector**: 10^15 W
- **γ-ray source (AIST)**: 10^16 W
- **HERCULES**: 10^17 W
- **Vulcan**: 10^18 W
- **X-ray (U. Tokyo)**: 10^19 W
- **SNS Laser Stripping**: 10^20 W
- **Beam diagnostics**: Various facilities

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**Legend:**
- **LLNL PW**: Livermore Laser Acquisition
- **Vulcan**: Sandia National Laboratories
- **HERCULES**: Lawrence Berkeley National Laboratory
- **Gekko**: Advanced Photon Source
- **LOA**: Lawrence Livermore National Laboratory
- **X-ray (U. Tokyo)**: University of Tokyo
- **1 TeV Collider**: CERN
- **Project X Stripping**: Los Alamos National Laboratory
- **LCLS Photoinjector**: Lawrence Berkeley National Laboratory
- **γ-ray source (AIST)**: AIST
- **SNS Laser Stripping**: Spallation Neutron Source
- **Beam diagnostics**: Various facilities

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**Footnotes:**
- **LLNL PW**: Livermore Laser Acquisition
- **Vulcan**: Sandia National Laboratories
- **HERCULES**: Lawrence Berkeley National Laboratory
- **Gekko**: Advanced Photon Source
- **LOA**: Lawrence Livermore National Laboratory
- **X-ray (U. Tokyo)**: University of Tokyo
- **1 TeV Collider**: CERN
- **Project X Stripping**: Los Alamos National Laboratory
- **LCLS Photoinjector**: Lawrence Berkeley National Laboratory
- **γ-ray source (AIST)**: AIST
- **SNS Laser Stripping**: Spallation Neutron Source
- **Beam diagnostics**: Various facilities
Burst-mode laser system

- High-frequency mode-locked seed laser with micro-pulse width ~ 50 ps
- Pulse picker to select a portion (macropulse) of the seeder output
- Amplification of macropulse (100us – 1 ms) at a low repetition rate
- Harmonic generation for UV output
- Each micro-pulse has ~ MW peak power at UV
Continuum burst-mode laser amplifier
Burst-mode laser installed at SNS (2009)

~55 ps

2.5 ns
Negligible loss in photon-particle interaction
Optical ring cavity

Light source: mode-locked laser (80.5 MHz)
Cavity frequency: 402.5 MHz
Stabilization of optical cavity

Unlocked cavity

Locked cavity

Upper: input laser pulse
Lower: intra-cavity laser pulse
## Examples of optical cavity

<table>
<thead>
<tr>
<th>Finesse</th>
<th>Wavelength</th>
<th>Pulse Width</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>16000</td>
<td>657 nm</td>
<td>CW</td>
<td>Fortier et al, PRL 97 (2006) 163905</td>
</tr>
<tr>
<td>3000</td>
<td>800 nm</td>
<td>52 fs</td>
<td>Jones et al, PRA 69 (2004) 051803</td>
</tr>
</tbody>
</table>
Average power dropped more than 1000 times!

- Pulse Energy (J)
- Repetition Rate (Hz)

- 1 mW
- 1 W
- 1 KW
- 1 MW
- 1 GW

- FLASH Photoinjector
- LCLS Photoinjector
- Project X Stripping
- γ-ray source (AIST)
- SNS Laser Stripping

X-ray (U. Tokyo)
Play the same game for the laser acceleration?
High peak power laser technology - Chirped Pulse Amplification

http://www.engin.umich.edu/research/cuos/ResearchGroups/HFS/Experimentalfacilities/Chirped_Pulse_Amp.html
High average power is a real challenge!

Ultimately most ultrahigh-intensity applications will require high average power. …. average power is a serious difficulty that will have to be surmounted for real world applications.

A simple analogy

<table>
<thead>
<tr>
<th></th>
<th>Wall-plug to HV power supply</th>
<th>Power supply to RF cavity</th>
<th>RF cavity to Beam</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm Linac</td>
<td>90%</td>
<td>50%</td>
<td>15-20%</td>
<td>5-10%</td>
</tr>
<tr>
<td>SCL</td>
<td>90%</td>
<td>50%</td>
<td>90%</td>
<td>~40%</td>
</tr>
<tr>
<td>Laser Driven</td>
<td>Wall-plug</td>
<td>Laser to plasma wave</td>
<td>Plasma wave to beam</td>
<td>total</td>
</tr>
<tr>
<td></td>
<td>20-50%</td>
<td>50%</td>
<td>40%</td>
<td>4-10%</td>
</tr>
</tbody>
</table>
High efficiency, compact pump lasers

41KW laser diode stacked array

Wall-plug efficiency: 60%

50 KJ Flashlamp

Wall-plug efficiency: 10%
Novel gain material – ceramic lasers

- Nd:YAG ceramic laser reached 40% efficiency
- High damage threshold
- Scaling to large aperture (1m x 1m): effectively no limit

Power scaling via beam combining

• An approach to building high-power lasers is to use arrays of relatively lower power lasers.
• Incoherent beam combining - a method of scaling up the laser power via multiplexing in position, angle, wavelength or polarization
  – total beam from the laser array cannot exceed that of each individual beam
• Coherent beam combining – all lasers occupy the same elements in phase space and behave as if they came from one coherent source.
  – Only coherent superpositioning allows truly scalable output powers and diffraction-limited quality of the combined beams
100KW Coherently Combined Lasers (Northrop Grumman)

From McNaught et al, in OSA FIO2009, paper FThD2 (2009)
Summary

• Laser-based nonintrusive beam diagnostics – Lasers are off-the-shelf. Engineer efforts for operational service.

• Photoinjectors, inverse Compton scattering, laser stripping – Key technical elements (mode-locked laser, burst mode amplifiers, optical cavity) are well understood. There is a clear path for development.

• Laser driven acceleration (wakefield plasma acceleration, ion acceleration) - basic concept demonstrated with ultra-short ultra-intense CPA lasers. Future development (e.g. new pump, new gain media, beam combining) needed to overcome average power requirement.