Laser work and related research at A0, SMTF/ILC

by ---- Jianliang Li
Outline

• Recent upgrade of the laser system at A0
• Future upgrade of the laser system for SMTF
• EO sampling for real time diagnostics of electron bunch
• Laser acceleration of electrons
• Laser system for polarized electron source at ILC
Recent laser work done at A0

• Overview and design of the new laser system
• Characterization of the seed laser and performance of the upgraded system
• Pulse stacker, single shot autocorrelator and long pulse train
Layout of the new laser system

Diagnostic table (CWAC and OSA)

D.S.

Seed laser

2-Pass

f₁ = 1 m

f₂ = 1 m

f₃ = 1 m

w₀ ~ 1 mm

Multi-Pass

P.P.

12"

4 feet

8 feet
Crystal table

from 2P

\( f_3 = 1 \text{m} \)

14"

\( f_4 = 1 \text{m} \)

S.F.

\( f_5 = 0.2 \text{m} \)

\( f_6 = 1 \text{m} \)

UV target
UV imaging system was designed to relay image in laser room to photocathode.

The UV transport line is in vacuum. The magnification of the lens is around 1.4. This imaging system allows us to control the UV pattern on photocathode in laser room.
New seed laser was purchased from Time-Bandwidth by Northern Illinois University.
Principle of SESAM laser

Semiconductor Saturable Absorber Mirror (SESAM) makes a passive mode-lock cavity. Nd:YLF crystal is pumped by a diode laser. $P_{out} = 450$ mW, rep-rate=81.25 MHz, $\lambda \sim 1054$ nm.
Seed laser is characterized in both time and frequency domains

- **Time domain**
  - Auto-correlation
  - FWHM = 7.25 ps
  - Pulse = 5.12 ps

- **Frequency domain**
  - Optical Spectrum Analyzer
  - $\Delta \lambda_{\text{FWHM}} = 0.52\ \text{nm}$
Performance of MP amplifier shows a good exponential behavior

\[ Y = A_0 \times (3.1)^n \]

**Working point**
Amplitude fluctuations after M.P. are caused by the power supply.

The voltage instability of the power supply of M.P. is < 0.2%.

Power fluctuation is < 0.4%.

noise for each round trip < 0.8%.

\[ \text{Fluc}_{MP} = \sqrt{\text{Fluc}_{Pulse}^2 - \text{Fluc}_{Laser}^2} \]
Green and UV conversion efficiencies

More than 50% doubling efficiency is achieved. The saturation helps reduce Green fluctuation.

About 40% quadrupling efficiency is achieved! The saturation helps reduce UV fluctuation.
UV fluctuations are determined by M.P.
A 50 μm spatial filter is inserted to improve the UV transverse profile. The beam size is about 4.3 mm of FWHM.
Longitudinal profile of UV pulse

Streak camera measurement

Intensity (a.u.)

Time (ps)

FWHM = 5.4 ps
Final output has four pulses stacked with adjustable delays and the neighbors have orthogonal polarizations, which eliminates the interference of the pulses both transversely and longitudinally.
Flat top with four stacked pulses was achieved

Combination of four stacked pulses gives relative flat top. This will suppress the space charge induced emittance growth.
Principle of single shot auto-correlator

The time window is determined by the maximum delay of the two beams,

$$\Delta T_{\text{time\_window}} = \frac{\Delta L}{c} = \frac{20}{3} \cdot L \cdot \sin(\theta) = \frac{10}{3} \cdot D \cdot \tan(\theta)$$

where $\Delta T$ is in ps, $x$ and $D$ mm. Usually $\theta$ is a small angle $\sim 5^\circ$, implying a time window of 2 ps or so. It is not enough for our pulse length of 5 ps.
Tilted wavefront increases time window

A grating can be used to tilt the wavefront so that

$$\Delta T_{\text{time\_window}} = \frac{20}{3} \cdot L \cdot [\sin(\theta) + \sin(\theta')] = \frac{10}{3} \cdot D \cdot [\tan(\theta) + \sin(\theta') / \cos(\theta)]$$

If it is tilted by 45°. The time window becomes 12 ps about enough for the 5 ps pulse.
Setup of single shot auto-correlator

1, grating to tilt the wavefront of the laser beam; 2, 50% beam splitter; 3 and 4, mirrors coated for IR beams.

From technical report of Minioptic Technology Inc.
The FWHM was determined to be ~6.2 ps, which corresponds to 4.4 ps for single pulse. This is a little shorter than 5.4 ps UV pulse measured by streak camera. The discrepancy is caused by the non-uniform transverse profile of the input beam.
Long pulse train I

800 µs

800-seed-pulse train

1 µs

Amplified 10-pulse train
Long pulse train II

- Amplified 400-pulse train (400 µs)
- Amplified 800-pulse train (800 µs)
Future upgrade of the laser system for SMTF

- Laser requirements of SMTF
- Further upgrade of the laser system
- Construction of transverse flattop beam
- Filling 4 successive RF accelerating buckets
### Laser requirements of SMTF

<table>
<thead>
<tr>
<th>Parameters</th>
<th>A0</th>
<th>SMTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pulse length</td>
<td>~0.8 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>&gt;4 nC</td>
<td>3.2 nC</td>
</tr>
<tr>
<td>Charge stability</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Micro bunch distance</td>
<td>1000 ns</td>
<td>337 ns</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>~800</td>
<td>up to 2820</td>
</tr>
<tr>
<td>Pulse rep-rate</td>
<td>1 Hz</td>
<td>up to 5 Hz</td>
</tr>
</tbody>
</table>

We need to increase the number of bunches in each pulse train and the duty cycle and reduce the distance between bunches.
Long pulse train with high rep-rate

Increase pulse length from 800 µs to 1 ms.

Decrease the bunch spacing from 1 µs to 337 ns.

Make it happen five times per second (Nd:YLF has five times larger thermal conductivity than Nd:glass).

Make the long train flat (pre-shaping and Optical Limiting).
Besides pre-shaping, optical limiting effect can reduce the intra-train fluctuation.

From Quan Gan et al., Optics Express, Vol. 13, No. 14, 5424(2005)
New schematic design for future upgrade of the laser system

Trigged at 3 MHz with 1 ms gate.

1. All the optics should be installed on one optical table.
2. Flash pumped Nd:glass M.P. should be replaced by diode pumped Nd:YLF.
3. The pulse picker must be triggered at 3 MHz with 1 ms gate and 5 Hz rep-rate.
4. Coupling of seed laser to amplifiers must be redesigned.
5. Another P.P. is needed to increase extinguish ratio and reduce beam loading.
Shaper converts Gaussian beam to flattop

Input size is fixed and not good for long distance transport (> 20 m).

From http://www.mt-berlin.com/frames_home/shaper_descr.htm
Modified pulse stacker can fill 4 successive RF accelerating buckets.

Delaying each pulse by 769 ps, we can fill 4 successive RF accelerating buckets. It is very doable in laser room to separate the pulses by 23 cm, but more thoughts are needed to design experiments that can take this advantage.
Single shot EO sampling for real time diagnostics of electron bunch length

- Principle of EO sampling
- EO sampling with spectral decoding
- EO sampling with temporal decoding
- EO sampling with spatial decoding
- BPM with sub-picosecond time resolution
Principle of EO sampling

No external electric field, no EO effect, no output \( T = \frac{I_{\text{out}}}{I_{\text{in}}} = 0 \).

Under external electric field, EO effect introduces phase delay between two polarizations of the laser beam. The phase delay can be determined by the measured \( T \).
Single shot EO sampling with spectral decoding

Limitations of spectral decoding

\[ T_{\text{det}} = \sqrt{T^4 + T_{\text{min}}^{-2}} \quad T_{\text{min}} = (T_C T_0)^{1/2} \]

**Fig. 1.** Variation of detected pulse length versus input pulse length for strong signals.

From J. R. Fletcher, Optics Express, Vol. 10, No. 24, 1425(2002)
Single shot EO sampling with temporal decoding

EO sampling with spatial decoding

BPM with sub-picosecond time resolution (dream on!)
Laser acceleration of electrons

• Open iris-loaded structure
• Diagram of laser acceleration
• Generation of $\text{TE}_{01}^*$ “donut” mode
• Theoretical simulations
Eigenmode of open iris-loaded structure gives longitudinal field for acceleration

The fields associated with TEM mode are given by,

\[ E_z(r, z, t) = \hat{E} J_0(k_r r) \exp(i(k_z z - \omega t)) \]
\[ E_r(r, z, t) = Z_{TM} H_\phi = -i \frac{k_z}{k} \hat{E} J_1(k_r r) \exp(i(k_z z - \omega t)) \]

where, \( \hat{E} \) is the axial peak electric field, \( k = n \omega / c \).

The phase velocity of the wave is,

\[ v_\phi = \frac{\omega}{\mathfrak{R}(k_z)} \approx \frac{c}{n} \left[ 1 + \frac{1}{2} \left( \frac{p_{10} \lambda}{2 \pi a} \right)^2 \right] \]

Where \( \lambda \) is the wavelength, \( J(p_{10}) = 0 \), \( n \) refractive index and \( c \) speed of light.
The chamber is filled with gas to compensate the phase slippage.
\( \text{TEM}_{01}^* \) donut mode has been generated at A0 with a Mach-Zender interferometer from re-gen.

R. Tikhoplav et al., Proceedings of EPAC 2002, Paris, France
Simulation with single electron

Parameters:
2a=1mm;
$\alpha > \lambda / a$;
Elements #: 50
L=2mm;
$\lambda = 1054$ nm;
$E_{\text{laser}} = 20$ mJ;
Pulse length=2ps;
Simulation with electron bunch

Evolution of the energy spectrum for electron bunch with various beam size propagating in the laser field.
Laser system for polarized electron source

- Principle of GaAs photoemission
- Laser parameters for ILC
- Prototype laser system based on Ti:Sapphire
Negative electron affinity (NEA) in GaAs
In strained GaAs energy levels split

(a) Bulk GaAs

(b) Strained GaAs

Left circularly Polarized photon

\[ E_g = 1.42 \text{ eV} \]

\[ -\frac{3}{2}, -\frac{1}{2}, \frac{1}{2}, \frac{3}{2} \]

Polarization is at best 50%.

\[ E_g = 1.46 \text{ eV} \]

\[ -\frac{3}{2}, -\frac{1}{2}, \frac{1}{2}, \frac{3}{2} \]

Polarization could be close to 100%.
Most recent results on polarization and quantum efficiency in strained GaAs

Nagoya (MOCVD)

Polarization 85 – 90%
QE 0.5 – 1%

From Takashi Maruyama, KEK ILC workshop (2004).
### Laser parameters recommended for ILC

<table>
<thead>
<tr>
<th>Laser parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-pulse energy at photocathode</td>
<td>~3 (1.5) µJ</td>
<td></td>
</tr>
<tr>
<td>Micro-pulse length</td>
<td>~2 ns</td>
<td></td>
</tr>
<tr>
<td># micro-pulse per train</td>
<td>2820 (5640)</td>
<td>Number</td>
</tr>
<tr>
<td>Intensity jitter</td>
<td>2 % (rms)</td>
<td></td>
</tr>
<tr>
<td>Micro-Pulse spacing</td>
<td>337 (169) ns</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>5 Hz</td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>750-850 nm</td>
<td></td>
</tr>
</tbody>
</table>

*From WG3a ILC Electron Source Recommendation*
Similar laser system was built at DESY.

Longer pulse and higher rep-rate are needed.

Longer train and more wavelength range are needed.

From I. Will, et al., Status Sep. 2004
In summary, the recent laser work done at A0 has been reviewed. A commercial seed laser purchased by NIU replaced the home-made oscillator. The performance of the new laser system is improved remarkably. Several future research fields, including drive laser system for SMTF, EO sampling for beam diagnostics, laser acceleration of electrons and drive laser for ILC, have been discussed too.
Figure 2.7: Schematic drawing of the continuous-wave autocorrelator (CWAC). The input beam (A) is divided by a beamsplitter (B) into a fixed arm and a variable delay arm on a rotating platform (C). The beams are crossed at a focus in a LiIO₃ crystal (D), and the green light is detected by a photomultiplier tube (F) after an infrared-blocking filter (E).
Beam match between seed laser and multi-pass cavity

A lens with focal length of 60cm is inserted so that the seed beam is matched to the eigen mode of the multi-pass cavity.
A plano-aspheric lens pair to convert a Gaussian to a flattop beam

From Paul Bolton’s talk at ANL, Feb. 18 2005.
Large gain for Nd:YLF diode pump laser

With diode pump and Nd:YLF crystal, amplification of up to 6,000 was achieved after a 4-pass amplifier.

Micro-bunching effect
Difficulties at A0 and future improvements

- The stability of seed laser caused the poor repeatability of TEM\(_{01}^*\) mode.
- The new seed laser should solve it (hopefully).
- The electron energy is only 15 MeV, too low for significant acceleration.
- At SMTF, the electron energy will exceed 200 MeV.
- Laser intensity is not yet 20 mJ.
- Another amplifier after re-gen is needed.
- Laser beam can not be compressed and sent to cave.
- At SMTF, another IR transport line should be installed so that the laser pulse is transported and compressed and then the TEM\(_{01}^*\) is produced.
Schematic diagram of the strained photocathode structure

GaAs Surface Layer

Active Layer

GaAs$_{1-x}$ P$_x$

Graded GaAs$_{1-x'}$ P$_{x'}$

x' = 0 --> x

GaAs Buffer Layer

GaAs Substrate

Dopant Concentration (cm$^{-3}$)

$5 \times 10^{19}$

$5 \times 10^{17}$

$5 \times 10^{18}$

$5 \times 10^{18}$

$5 \times 10^{18}$

$5 \times 10^{18}$