Adaptive 3D- Laser pulse shaping System to
Minimize Emittance for Photocathode RF gun
~ toward to the highest brightness of electron beam source ~

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1. Introduction ~ SPring-8 Photocathode RF gun ~
2. Motivation for 3D-laser pulse shaping
3. Strategy of 3D-laser pulse shaping
4. Optimization system of 3D-Laser pulse
   - Automation with DM + Genetic Algorithms
   - UV-Pulse Stacker (macro) + DAZZLER (micro)
5. Emittance measurements
6. Summary and future plan
1. Introduction

1-1 History of SPring-8 Photocathode RF gun

1996 Study of photocathode RF guns started for the next generation photon source
1999 First beam test with YLF laser system
2002 Emittance $2.3\, \pi \text{mm mrad} \, @0.1\, \text{nC}$ (pulse width: 5 ps) with homogenizing in Spatial profile (using Microlens array)
  Cartridge type cathode development started.
2003 New gun & laser test room constructed and an accelerating structure installed.
2004 Maximum field of 190 MV/m at cathode
  Laser was stabilized with 0.2% (rms @0.3TW fundamental) for 1.5 Month (Laser Oscillator itself: 0.3% p-p for 4.5 months)
2006 3D-laser shaping system was completed.
  Emittance $1.4\, \pi \text{mm mrad} \, @0.4\, \text{nC}$ (pulse width: 10 ps) with 3D-Cilindical laser pulse (Flattop SP (DM); Square TP (UV-PS))
2007 Axicon lens pair-hollow beam incidence system with 3D-laser shaping was developed.
1. Introduction

1-2 Characteristics of SPring-8 RF gun

1. Laser
   - Spatial profile control: Homogenizer (or Deformable Mirror)
   - Temporal distribution: UV-pulse stacker (or SLM)

2. Synchronization of Laser & RF (PD with bandpass filter)
   - RF generation (2856 MHz) from laser pulses (89.25 MHz)
   - RMS jitter (@low level) < 100 fs

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Normalized Emittance $[\pi \text{ mm mrad}]$ vs. Charge/Bunch [nC]

- 2002
- 2006

SPring8-type RF gun cavity
The max. field 190 MV/m
Present stability:

\[
0.2 \sim 0.3 \% \text{ (rms) at Fundamental}
\]

Long Term: ~ the most stable TW System ~

1.5 months continuously limited by lifetime of flashlamp

New Oscillator system has been contiguously operated for 10 months.

After Passive control

\[
5 \sim 10 \% \text{ (rms)} \rightarrow 0.95 \sim 1.4 \% \text{ (rms)}
\]
1-4. Laser Oscillator 4.5 months continuous operation

- All active Auto-Pumping direction & Cavity length correction

24 hours, 4.5 months long continuous operation:
- Laser output (< 0.3 % p-p)
- Spectrum
- Spectral bandwidth;
- Central wavelength;
- Distribution

*are stable!*

24 hours, 10 months long continuous operation was done. (< 1 % p-p)

- Repetition rate of Laser Oscillator was locked at 89.25 MHz (89250000.00 Hz).
- It is stable within 0.01 Hz (Reference with Rb atomic clock)
1-5. RF- Regeneration & Synchronization System
(Direct conversion with PD & bandpass filter)

Laser side:
- Laser pulse train @ 89.25 MHz
- Laser Osc @ 89.25 MHz
- Piezo Mirror
- Photo Diode
- 2856 MHz RF OSC
- 4th Harmonic Bandpass Filter
  - Auto-gain control
  - Loop on/off
  - Phase Detector @ 357 MHz
  - Loop Gain Bandpass Filter
- 8 Divider

Accelerator side:
- Photocathode RF GUN
- Klystron
- RF modulation amplifier
- RF signal @ 2856 MHz
- Amplified & compressed Laser Pulses @ 790nm, 10 Hz
- Phase shifter
- THG
- Laser Pulses light source @ 263nm, 10 Hz
- Timing signal @ 10Hz
- YAG laser @ 10Hz
- Pump laser @ 10Hz
- Ti:Sa amplifier @ 10Hz
1. Introduction

1-6. Laser & RF Synchronization
(Direct conversion with PD & bandpass filter)

Time delay between RF signal & Laser pulse measured with Tektronix TDS8200 Sampling Oscilloscope

- RMS Jitter < 100fs
- Laser Pulse

RF signal
SPring-8 Photocathode RF gun test facility

RF Gun
Accelerating structure
Single cell pill-box cavity RF gun
Cartridge-type cathode RF Gun
Emittance monitor

WEPPH022, H. Tomizawa, Z-Pol RF gun
Yearlong maintenance-free laser system

Present status of Laser System in humidity (55%) -controlled clean room

Laser System after passive stabilization with Temperature-control Plate

Oscillator with auto alignment
2. Motivation for 3D-laser pulse shaping

2-1. Ideal 3D-laser profile: Cylindrical or ellipsoidal?

\[
\sigma = \sqrt{\sigma_{SC}^2 + \sigma_{RF}^2 + \sigma_{Th}^2}
\]

Space charge effect: Nonlinear term should be suppressed.

1. Cylindrical
   If suppress non-linear term of space charge effect, the aspect ratio of the Laser Profile is important!

2. Ellipsoidal
   If the slice density is kept constant during acceleration, non-linear term will be suppressed!
3. Strategy of 3D-laser pulse shaping

3-1 3D-Laser pulse System

3D-Laser shaper:

1. Combination of Spatial shaper (2D) + temporal shaper (1D)
   1-a. Fixed shaping systems: MLA, pulse stacker
   1-b. Adaptive shaping systems: DM, SLM
       It should be no influence between both shaping technique!

2. Directory 3D shaping
   2-a. Fixed shaping systems: Fiber bundle, DOE
   2-b. Adaptive shaping systems: 2D-SLM

MLA: Micro Lens Array
DOE: Diffractive Optical Elements
SLM: Spatial Light Modulator
DM: Deformable Mirror
3. Strategy of 3D-laser pulse shaping

3-2 Ti:Sa Laser System Configuration

~ 50 fs- TW- Ti:Sa Laser System with 3D-pulse shaper ~
3. Strategy of 3D-laser pulse shaping

3-3. 3D- Laser Beam Shaping system

- UV- Laser source (total stability!)
  - Laser Pulse Energy: 1.4% @THG
  - Pointing Stability & Reproducible
  - Timing Jitter < 1 ps

- Temporal Profile:
  - Pulse duration: 2.5 - 20 ps
  - Gaussian
  - UV- Pulse Stacker

- Spatial Profile:
  - Distribution: Flattop
  - Deformable Mirror

- Pulse duration: 2.5 ps
- Pulse duration: 10 ps
- Diameter 1 mm

DAZZLER

Pulse Stacker

10 pps

Deformable Mirror

Flattop

Streak Image of stacked pulses

~ present status at SPring-8 ~
3. **Strategy of 3D-laser pulse shaping**

3-4. **Directly 3D-shaping System**

**Fiber Bundle with computer-aided Deformable mirror**

**Profile Data**

- PC for control Deformable mirror and Evaluate resulting Laser Profile

**Electron Beam Profile**

**Video Signal**

**OR**

**CCD sensor (LBA-PC)**

**Laser Light source (THG: 263nm)**

**Fiber Bundle (0.5~1m)**

**Lens**

**Spatial shape**

**Temporal shape 16 ps (FWHM)**

**Deformable mirror**

**Control DM**

**Control DM**
4. Optimization system of 3D-Laser pulse

4-1. 3D- Laser Beam Shaping system

~ present status at SPring-8 ~

UV- Laser source (total stability!)

- Laser Pulse Energy: 1.4% @THG
- Pointing Stability & Reproducible
- Timing Jitter < 1 ps

Temporal Profile:
- Pulse duration: 2.5 ~ 20 ps

Spatial Profile:
- Distribution: Flattop
- Gaussian

Dazzler

Pulse Stacker (3 stages)

Pulse Stack: 10 pps

Pulse duration: 10 ps

Pulse duration: 2.5 ps

Diameter: 1 mm

UV- Pulse Stacker

Flattop

Deformable Mirror

Deformable Mirror

Streak Image of stacked pulses
4. Optimization system of 3D-Laser pulse

4-1. 3D- Laser Beam Shaping system

~ present status at SPring-8 ~

DAZZLER: micro pulse shaping

THG

UV-Pulse Stacker: macro pulse shaping

Deformable mirror: transverse shaping

Normal incidence to the cathode

DAZZLER AO-Modulator (micro pulse shaper)

+ Fundamental => THG (micro) pulse
4-2. Spatial profile shaping with DM

4-2-1. Deformable Mirror

- Deformation Steps: 256 \((0 \sim 255 \text{ V})\)

**Merit:** *adjustable and actively controllable!!*

**Demerit:** *too many Possibility: \(256^{59} \sim 10^{141}\)*

→ **Necessity of special algorithm to optimize**

- Genetic + Neuron model Algorithm

- Al-coated SiN-Membrane
  \((R > 70\% \text{ in UV after 1 week})\)

- Hexagonal elements
  \((59 \text{ channels})\)

**Note that:** *Membrane is very delicate!!*

*We build dry N\(_2\)-Housing for DM.*
4-2. Spatial profile shaping with **DM**

4-2-2. Deformable Mirror Actuator (ex. 37ch)

**Voltage:** 0 ~ 255 V

**Probability:** 256 $^{59} \sim 10^{141}$ for 59ch (in our case)

**Actuator:**

Initial State (All: 0V)

All: 125V

All: 255V (Max. Voltage)

Random Voltage
Genetic Algorithm

<Basic Process>

1) Coding: Digitize control parameters
   gene: 1 0 1 1 1 0 0 0

2) Initialization: prepare a sets of gene

3) Basic Process

- Initial gene
- Selection
- Crossover
- Mutation
- Change gene sets
- Evaluation
Fitting Function to evaluate Flattop profiles

Laser profile during optimization

(Laser beam profiler : LBA-PC)

Fitting function: weight (a, b, c, d, e, f, g, h, i)

\[ f(\text{profiles}) = a + b + c + d + e + f + g + h + i \]

1. **Top Hat Factor**: Maximize the Top Hat Factor (0 ~ 1)
2. **Effective Diameter**: Minimize the difference between the diameters of set circle and measured
3. **Flatness (Std Dev/mean)**: Minimize the standard deviation divided by the average in a flattop area
4. **Aperture Fraction**: Maximize the integrated energy within the set circle area
5. **Peak-to-peak**: Minimize the difference between the max. and min. in a flattop area
6. **Hot Spot (max.)**: Minimize the max. in a flattop area
7. **Dark Spot (min.)**: Maximize the min. in a flattop area
8. **Beam Center**: Minimize the difference from the initial center position (x, y)
9. **Beam Diameter**: Minimize the difference from the set diameter

Intensity distribution (cross section)
Weight of each term of fitting function for **Flattop**

~ decided by comparing convergence status ~

<table>
<thead>
<tr>
<th>Term</th>
<th>Meaning</th>
<th>Absolute convergence value with 500step</th>
<th>System Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top Hat Factor</td>
<td>0.5</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Maximize the Top Hat Factor (0 - 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Flattop: THF = 1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Effective Diameter</td>
<td>25</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Minimize the difference from the diameter of set circle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Flatness (SD/mean)</td>
<td>0.2</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>Minimize the standard deviation divided by the average in a flattop area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Aperture Fraction</td>
<td>0.8</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Maximize the integrated energy within the set circle area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Peak-to-peak</td>
<td>60</td>
<td>1 (norm)</td>
</tr>
<tr>
<td></td>
<td>Minimize the difference between the max. and min in a flattop area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Hot Spot (max.)</td>
<td>(60) same as Peak-to-peak</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Minimize the max. in a flattop area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Dark Spot (min.)</td>
<td>(60) same as Peak-to-peak</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Maximize the min. in a flattop area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Beam Center</td>
<td>5</td>
<td>12</td>
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<tr>
<td></td>
<td>Minimize the difference from the initial center position (x, y)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Beam Diameter</td>
<td>25</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Minimize the difference from the set diameter</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Closed Control System for experiment
4-2. Spatial profile shaping with DM
4-2-4. Results of the combination DM GA

This shaping with computer-aided DM was done @THG
⇒ Flattop shaping OK!

Computer-aided DM for UV (THG)
⇒ No problem for FHG (197 nm)

Auto-Shaping (1000 steps)
4-3. Temporal profile shaping (Pulse stacking)

4-3-1. UV-Pulse Stacker (macro pulse structure)

Input pulse (micro pulse) width is chosen to make flat stacked pulse (macro pulse) at the cathode!

Not that, laser pulse will be positively chirped & stretched through the silica material (laser transport optics)!

To avoid interferences on the plateau of stacked macro pulse, S- and P-polarized pulses are alternatively positioned!

IN : 2 ps

OUT : 20 ps
Changing 2\textsuperscript{nd} dispersion with AO (DAZZLER), 2.5-\text{ps} input pulse (micro pulse) is generated.

To avoid interferences on the plateau of stacked macro pulse, S- and P- polarized pulses are alternatively positioned!
Time chart of pulse stacking:

3 stages for generation of **20 ps** square macro pulse

If we mask the P-pulse at each stage; **Easily shift to 10 ps, 5 ps**
4-3-3. Temporal profile shaping (Pulse stacking)
4-3-3. Developed UV-Pulse Stacker

UV pulse stacker (0 ~ 3 stages)
Two 6.5-ps stacked sub-macro stricture 14 ps between them

Shifting optical delay 1

All stacked together 15.5 ps FWHM
Usage Photocathode with energy analyzer as a streak camera

Temporal shift between S & P

Spatial misalignment on the photocathode
UV-Laser after 3D-shaped with DM & Pulse Stacker

Electron Beam Profiler

Variable Down Collimator

AR- Entrance Window

Bending Magnet

Laser Powermeter

Electron Energy Analyzer

Laser Profiler

Laser Optical Transport & Monitors
Usage Photocathode with energy analyzer as a streak camera

Input micro pulse is too short! Micro pulse energy & intervals are not equivalently optimized!

Micro pulse width, energy, and intervals are optimized!

Stacked Pulse Duration: 20 ps
( Input pulse width @ cathode: 2.5 ps )
4-3. Temporal profile shaping (in Oct. 2007)

4-3-4. Fixed pulse stacking with birefringence crystal

UV-Pulse Stacker → UV-Pulse Stacking Rod

Design of crystal is fixed, installing in this Oct.

- Oscillator → Dazzler → Stretcher
- Amplifier → Compressor
- THG
- Pulse stacker

UV-pulse stacking rods

- α-BBO
- Angle of rotation
  - 45°
  - 20 mm ±0.1 mm (10 ps ±50 fs)
  - 70.37°
  - 45°
  - 10 mm ±0.1 mm (5 ps ±50 fs)
  - 35.19°
  - 5 mm ±0.1 mm (2.5 ps ±50 fs)
  - 17.6°

Optical Rotatory Dispersion (ORD); Kramers-Kronig relation
4-3. Temporal profile shaping (future planning)

4-3-5. Adaptive micro-pulse optimizing with 2 AO
- UV- & IR-DAZZLER feedback sys. + Pulse Stacker

Combination with DAZZLER shaping in IR, and UV pulse measurement with feedback loop.

Feedback loop will be done in 2008

Courtesy of Fastlite
5. Emittance measurements
5-1. 3D- Laser Beam Shape for experiment
~ present status at SPring-8 ~

Flattop : φ0.8 mm

Square pulse 20 ps

Q-scan emittance measurement

Laser normal incidence
5. Emittance measurements

5-2. low emittance electron beam generation

~ we can provide low emittance beam for a week ~

Accelerator system 26 MeV

Result of emittance measurement: $2.0\pi$ mm mrad 1.0 nC

Stacked pulse duration 20 psec

We are preparing experiment with further fine optimization of 3D-laser pulse for 1.5 month long.
5. Emittance measurements

5-3. Low emittance electron beam generation

- we are testing with different 3D-parameter -

Result of emittance measurement: \(2.0\pi \text{ mm mrad } \pm 1.0 \text{ nC}\)

Pulse duration: 20 ps

Some space charge limitation?

- 1.8\(\pi \text{ mm mrad } \pm 0.5 \text{ nC}; 15 \text{ ps}\)
- 1.4\(\pi \text{ mm mrad } \pm 0.4 \text{ nC}; 10 \text{ ps}\)

Normal incident mirror?

Q-scan fitting

\[\sigma = \frac{1.44 \pi \text{ mm mrad}}{10 \text{ ps}, 0.38 \text{ nC}}\]

\[\sigma = \frac{1.81 \pi \text{ mm mrad}}{15 \text{ ps}, 0.52 \text{ nC}}\]
6. Summary & future plan

A. We realized stable laser system
   - Oscillator: 24 hours, 10 months, non-stop
   - TW- Amp.: 24 hours, 1.5 months, non-stop
   - THG: 1.4% rms stability

B. Automatically shaping Spatial Profile with DM + GA was successful! (Gaussian or Flattop)
   - Arbitrary Laser Shaping
   - However, it takes 1 hour to optimize.

C. Square pulse generation with UV-pulse stacker was successful at THG (263 nm)!
   - Square Pulse: ~2 - 20 ps;
   - Rising-time: ~700 fs
6. Summary & future plan

D. Result of emittance measurement

- $2.0\pi$ mm mrad @ 1.0 nC; 20 ps
- $1.8\pi$ mm mrad @ 0.5 nC; 15 ps
- $1.4\pi$ mm mrad @ 0.4 nC; 10 ps

E. New incidence system

Hollow beam incidence

Normal incident mirror can be caused of difference bw X- and y-emittance.
DAZZLER AO-Modulator (micro pulse shaper)

+ Fundamental => THG (micro) pulse
Summary of Fiber Bundle Shaping

• Shaping with computer-aided deformable mirror could generate Flattop. It is very flexible to optimize the spatial profile (electron bunch) with genetic algorithm.

• Fiber Bundle is ideal as a 3D-shaper
  • It is very simple to shape: You have to optimize the length of the Bundle for aimed pulse duration: 15 ps ~ 1-m long
  • 3D-laser profile: It can generate ellipsoidal from any profile.
  • Short working distance: It needs to develop back illumination.
  • Laser fluence limit: Laser fluence @ 100 fs <1.5 mJ/cm²
    It is possible to use as 3D-shaper down to 60 nJ/pulse.

• Transparent cathode for shaping complex system with fixed fiber bundle & adjustable deformable mirror might have a lot of possibilities with fine tuning.
**Procedure (1 step): MGG (Minimal Generation Gap)**

1. Random select Parents and generate Children (Family)
   - Parents (Selected randomly from G)
   - Create 2 Children from the Parents

2. Drive Deformable mirror by Family and get results from Laser Profiler

3. Evaluate resulting parameter (Close to Flattop)
   - Resulted new order of priority: Child2 > Father > Mother > Child1
   - Selected!

4. The best two Chromosomes (Next Parents (i),(j))
How to create gene of child? (Crossover)

(1) 1 point Cross

Father  
Mother

<table>
<thead>
<tr>
<th>Child 1</th>
<th>Child 2</th>
</tr>
</thead>
</table>

Random length

(2) 2 point Cross

Father  
Mother

<table>
<thead>
<tr>
<th>Child 1</th>
<th>Child 2</th>
</tr>
</thead>
</table>

Random length

(3) Random Cross

Father  
Mother

Random Selection for 59 elements of parents
Create random value (0-1),
Over 0.5? Or Under 0.5?

Child 1
Child 2

(Child 2 = Child 1)

The reason to chose simple to program