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

2001 New Ti:Sapphire laser system installed.

2002 Emittance 2.3 πmm mrad @0.1 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 πmm mrad @0.4 nC (pulse width: 10 ps) with 3D-Cillindlical laser pulse (Flattop SP (DM); Square TP (UV-PS))

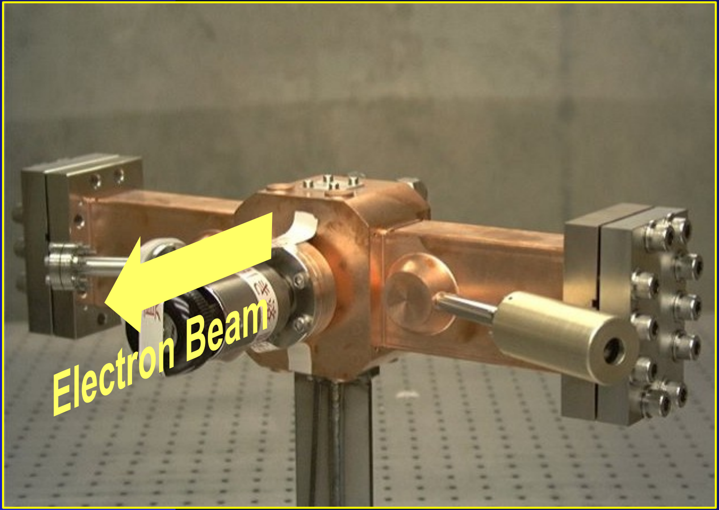
2007 Axicon lens pair-hollow beam incidence system with 3D-laser shaping was developed.

1. Introduction

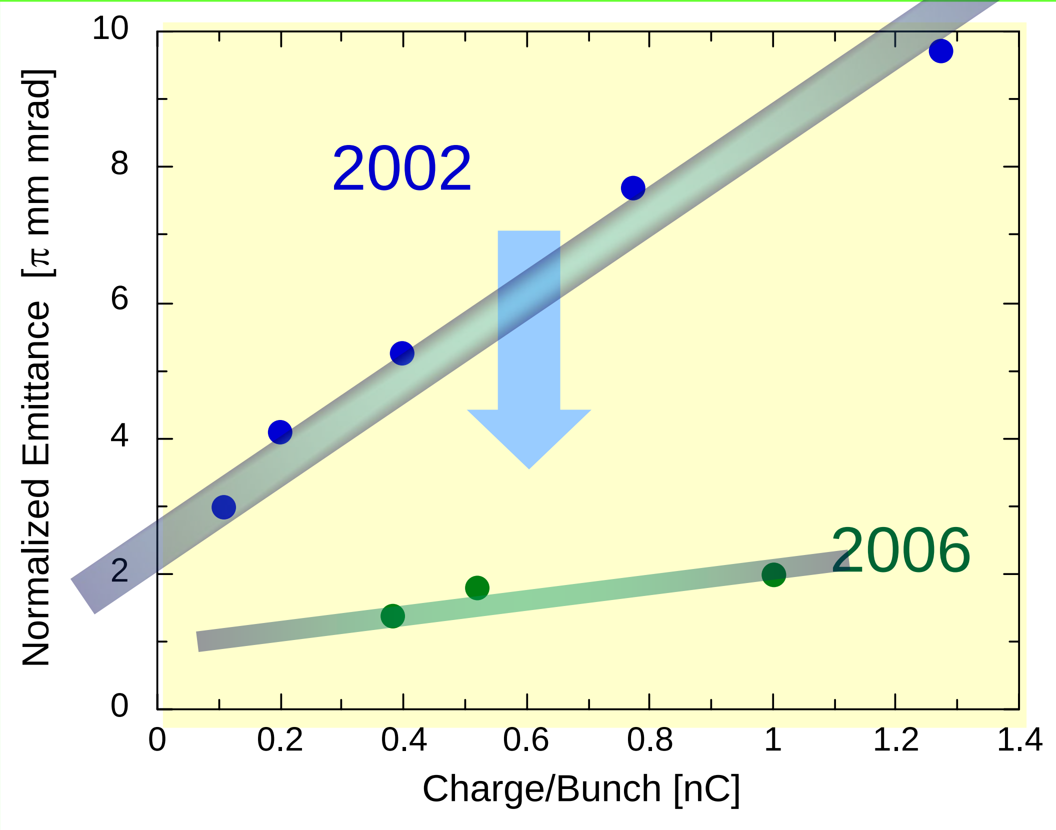
1-2 Characteristics of SPring-8 RF gun

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



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

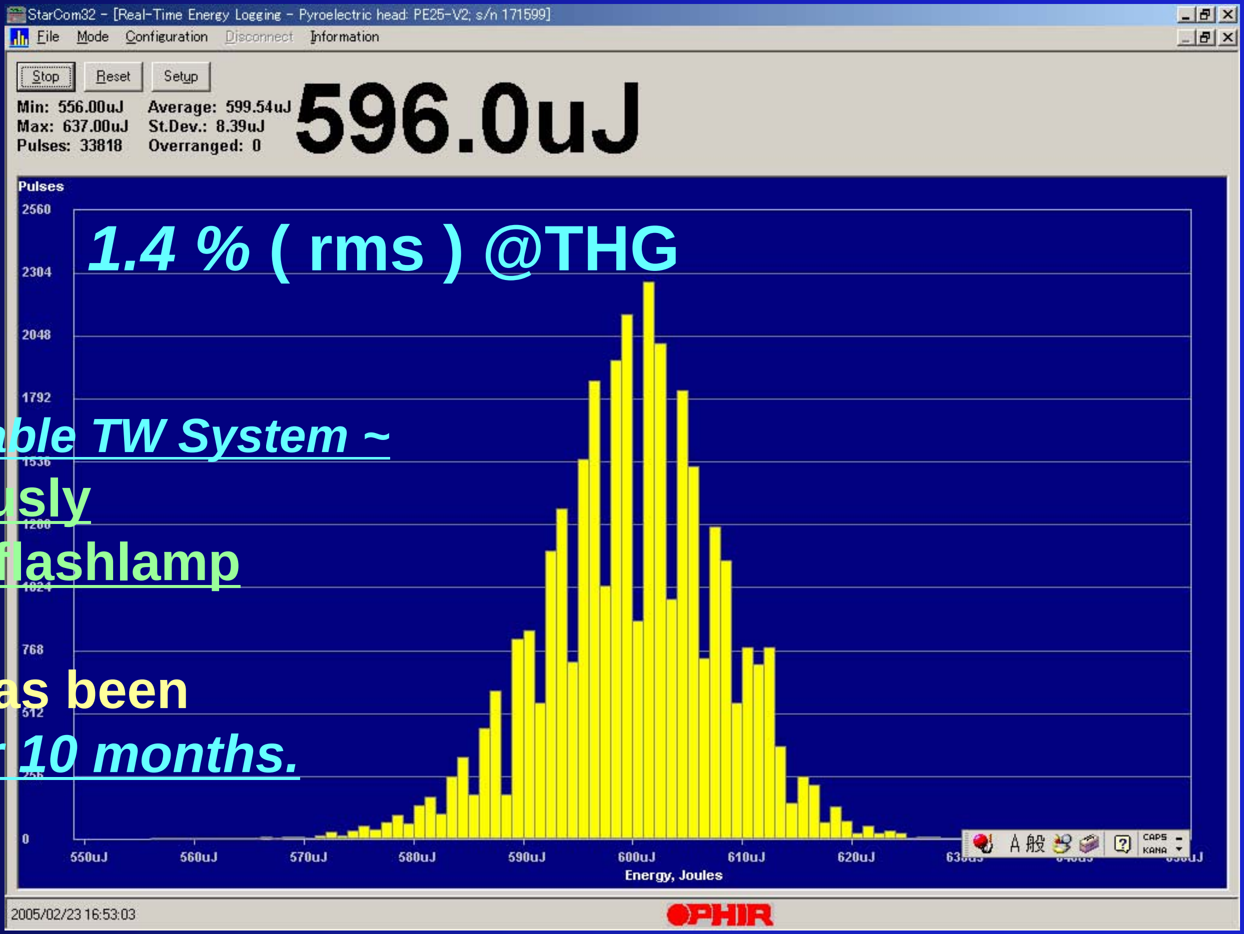


. Introduction

1-3. he present status of stability of UV-Laser

Present stability:

0.2 ~ 0.3 % (rms)
@ 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 ~ 10 % (rms) → *0.95 ~ 1.4 %* (rms)

1. Introduction

1-4. Laser Oscillator 4.5 months continuous operation

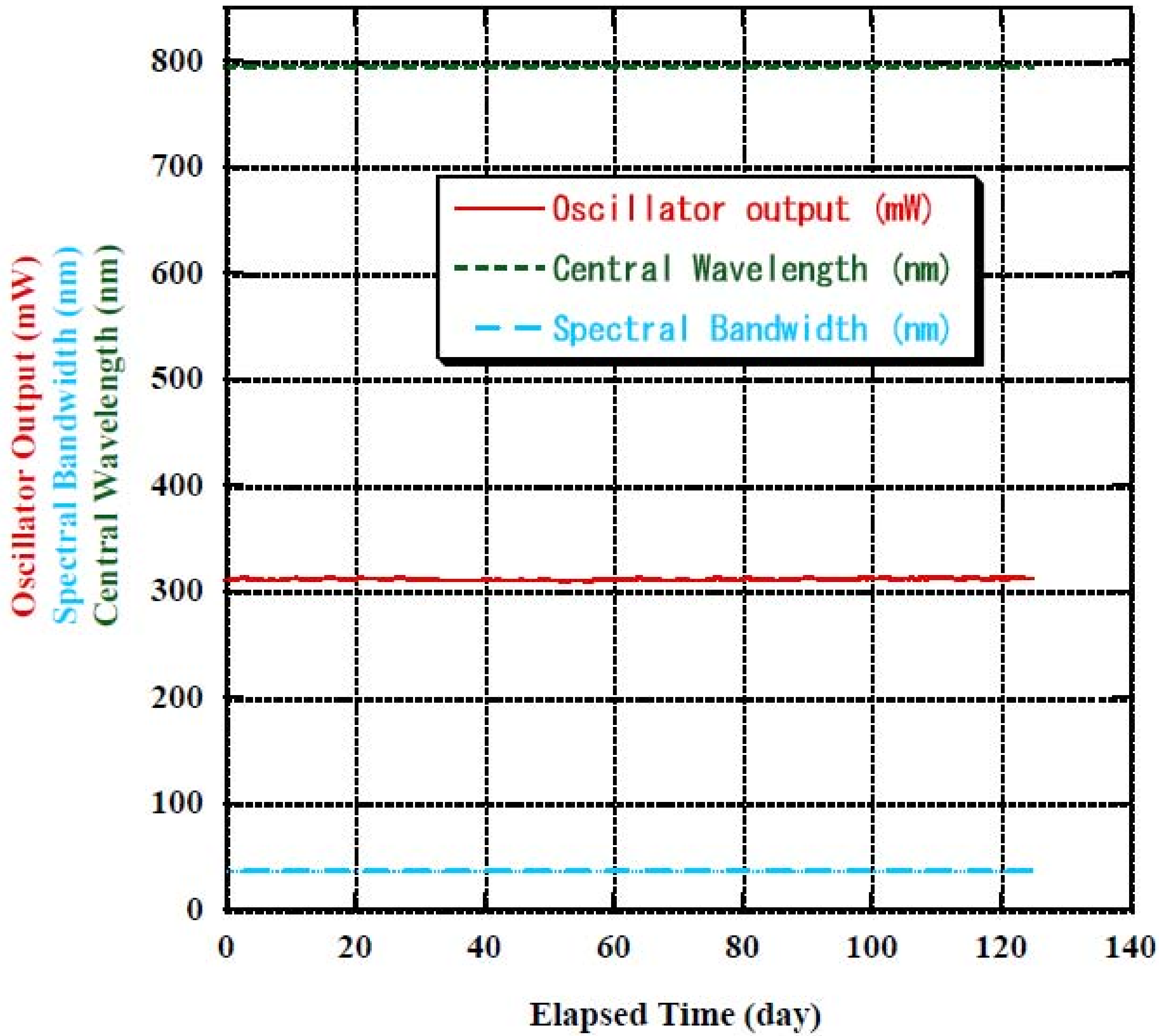
All active Auto- Pumping direction & Cavity length correction

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

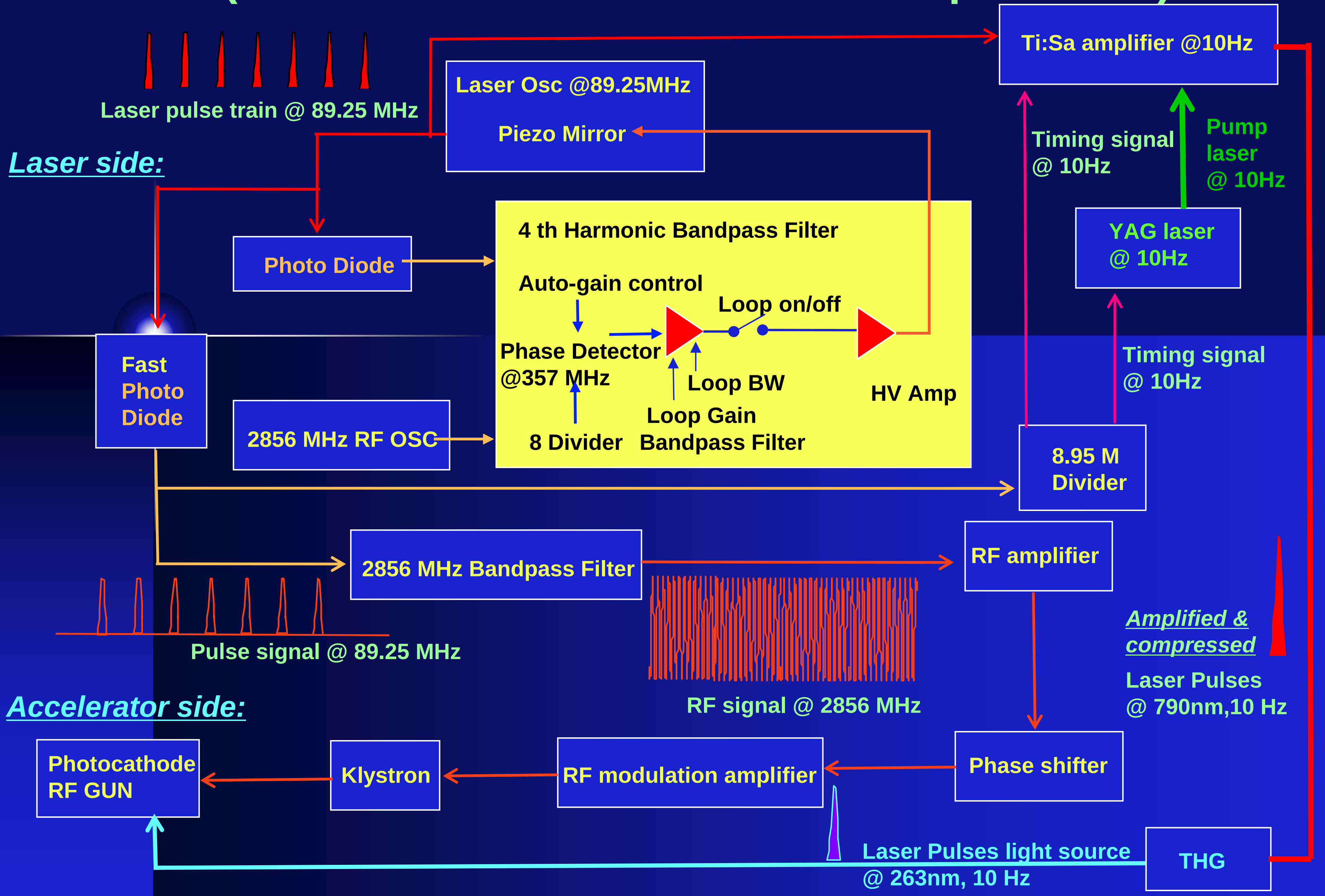
are stable !

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)



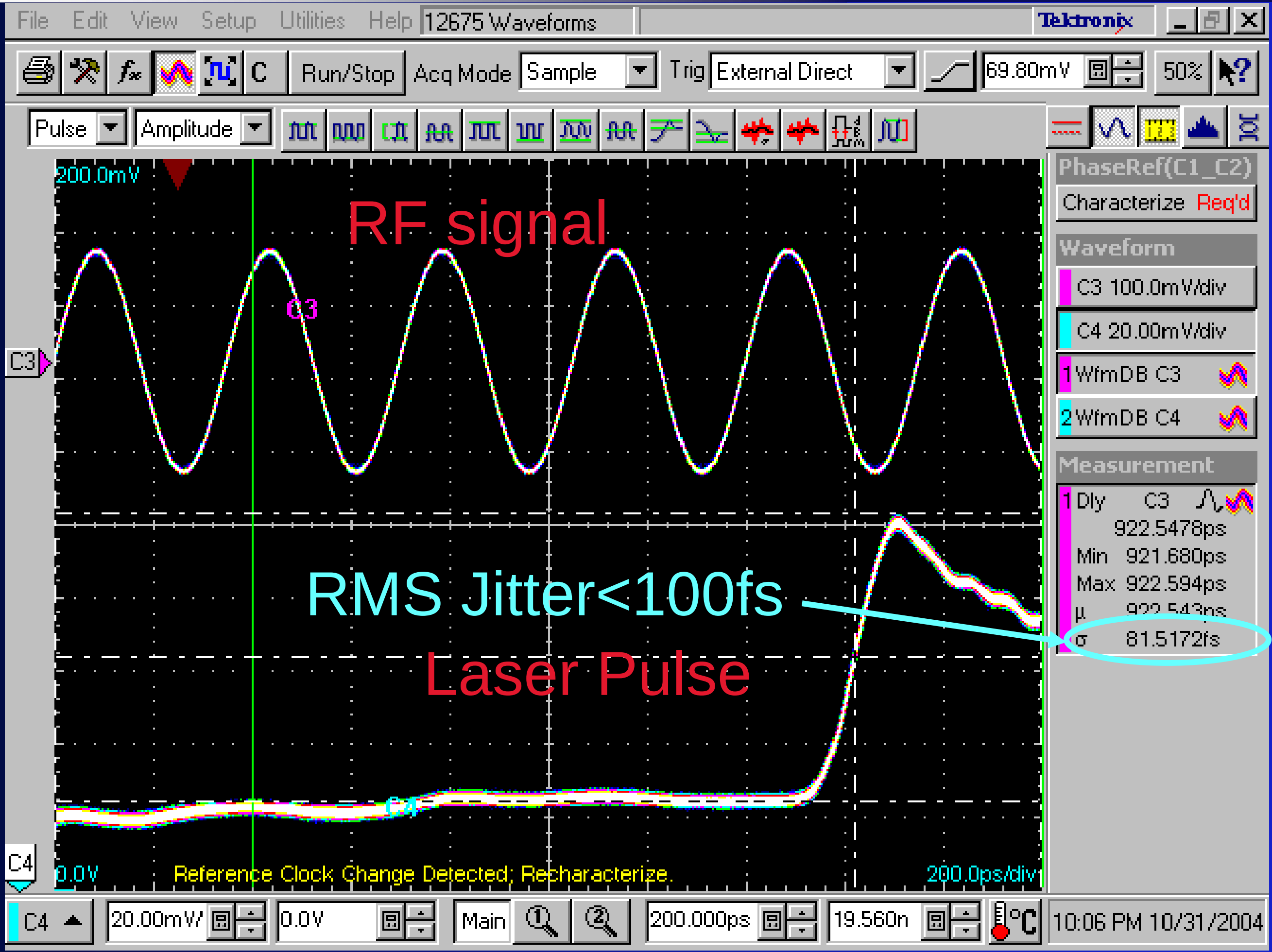
1-5. RF- Regeneration & Synchronization System
(Direct conversion with PD & bandpass filter)



1. Introduction

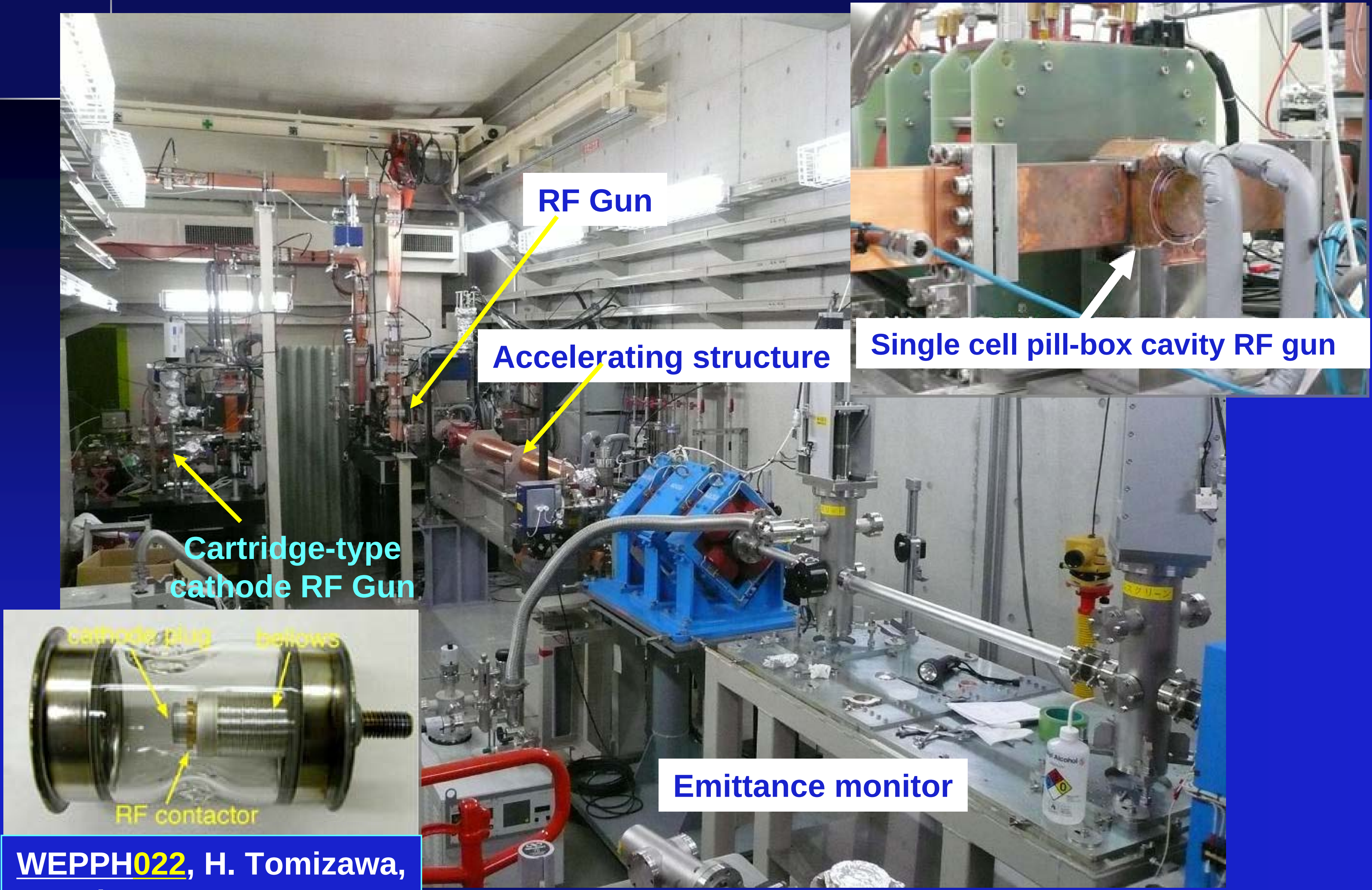
1-6. Laser & RF Synchronization

(Direct conversion with PD & bandpass filter)



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

SPring-8 Photocathode RF gun test facility



WEPPH022, H. Tomizawa, Z-Pol RF gun

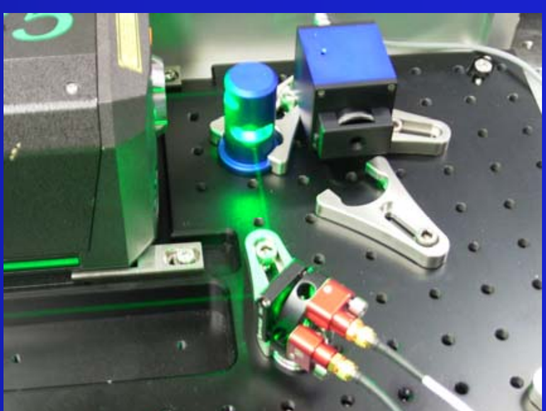
Yearlong maintenance-free laser system

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

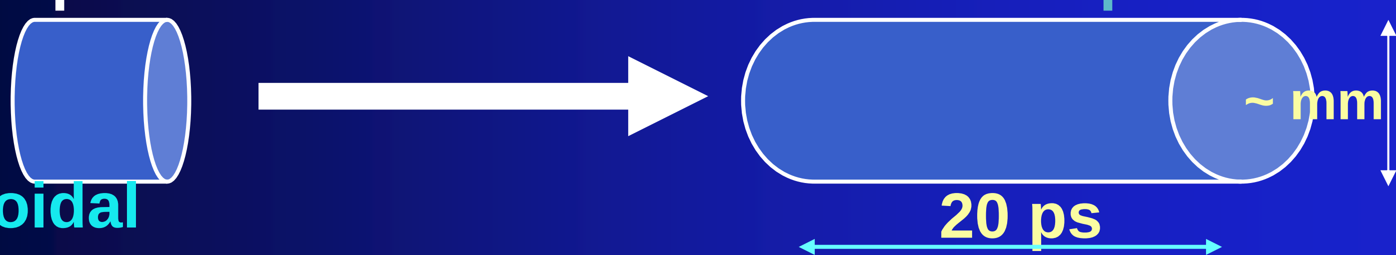
2-1. Ideal 3D-laser profile: Cylindrical or ellipsoidal?

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

***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

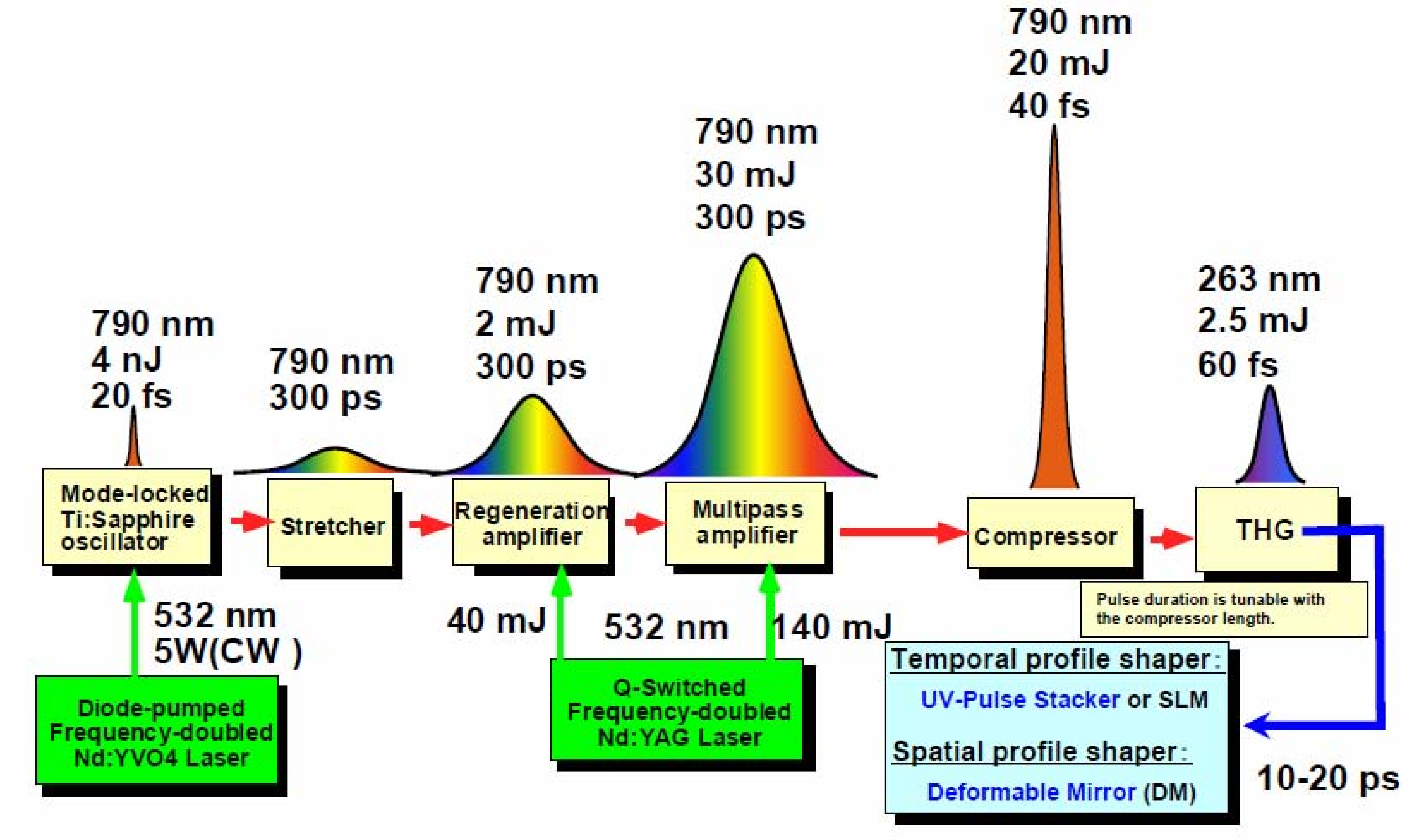
SLM : Spatial Light Modulator

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

~ 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

UV- Pulse Stacker

Spatial Profile:

Distribution: Flattop

Deformable Mirror

Gaussian

Pulse duration: 2.5 ps

Pulse duration: 10 ps

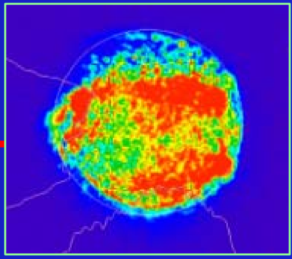
Diameter 1 mm

DAZZLER

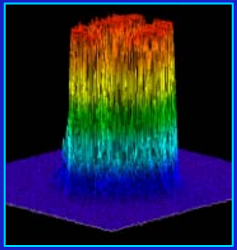
Pulse Stacker

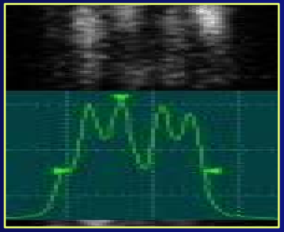
10 pps

Deformable Mirror



Flattop



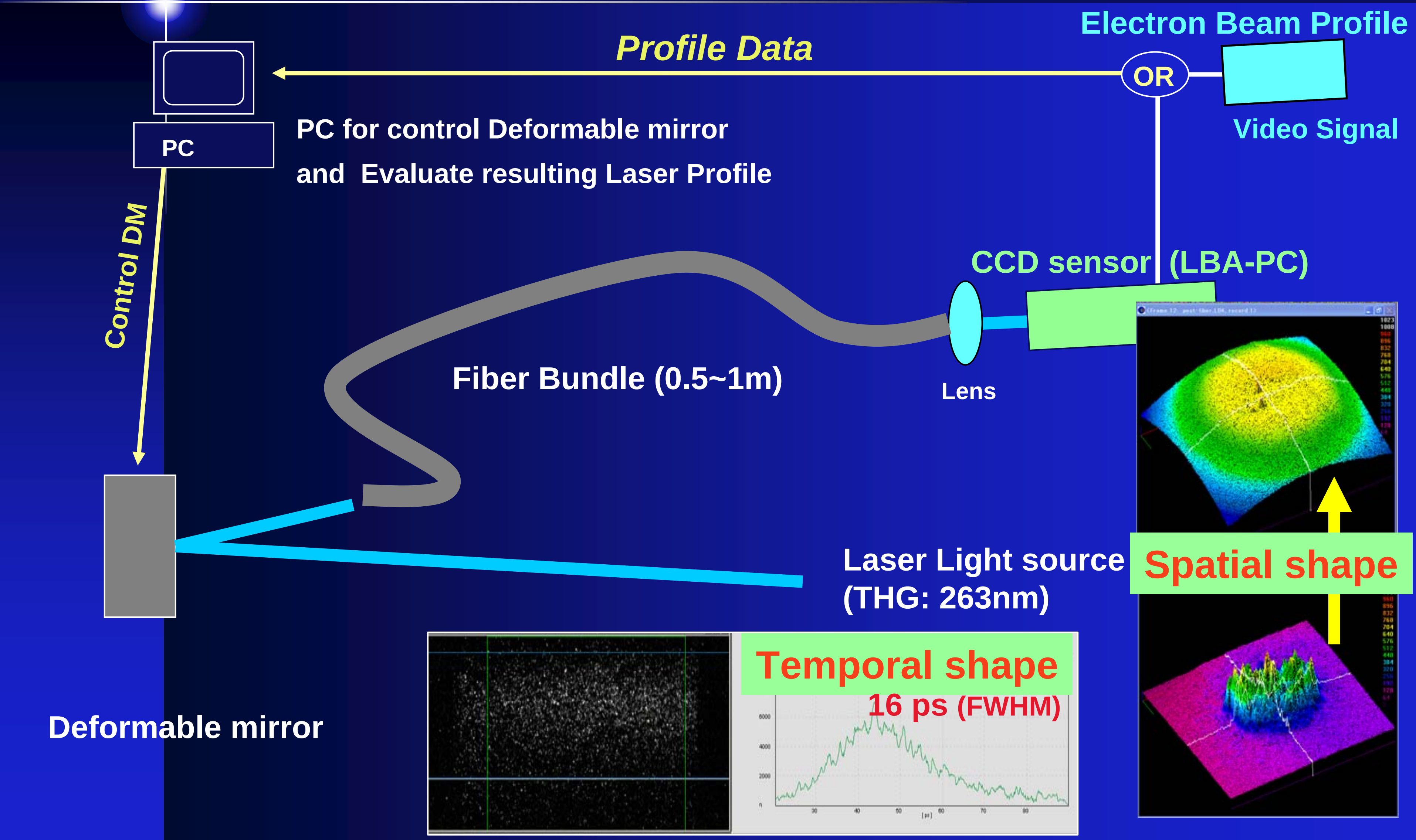


Streak Image of stacked pulses

3. Strategy of 3D-laser pulse shaping

3-4. Directly 3D-shaping System

Fiber Bundle with computer-aided Deformable mirror



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

Spatial Profile:

Distribution: Flattop

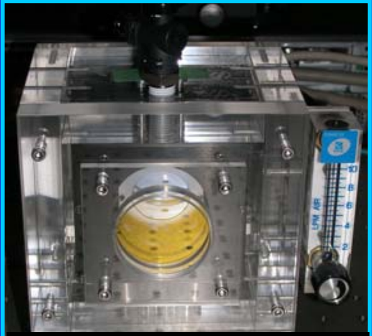
Deformable Mirror

Temporal Profile:

Pulse duration: 2.5 ~ 20 ps

UV- Pulse Stacker

Gaussian



Deformable Mirror

Pulse duration: 2.5 ps

Pulse duration: 10 ps

Diameter 1 mm

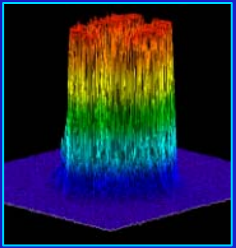
DAZZLER

Pulse Stacker

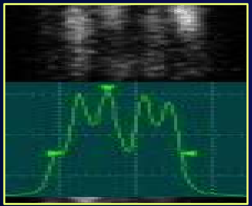
10 pps

Deformable Mirror

Flattop



Streak Image of stacked pulses



Pulse Stacker (3 stages)

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

4-2. Spatial profile shaping with DM

4-2-1. Deformable Mirror

~ Deformation Steps: 256 (0 ~ 255 V) ~

Merit: *adjustable and actively controllable!!*

Demerit: *too many Possibility*: 256^{59} ~10^{141}

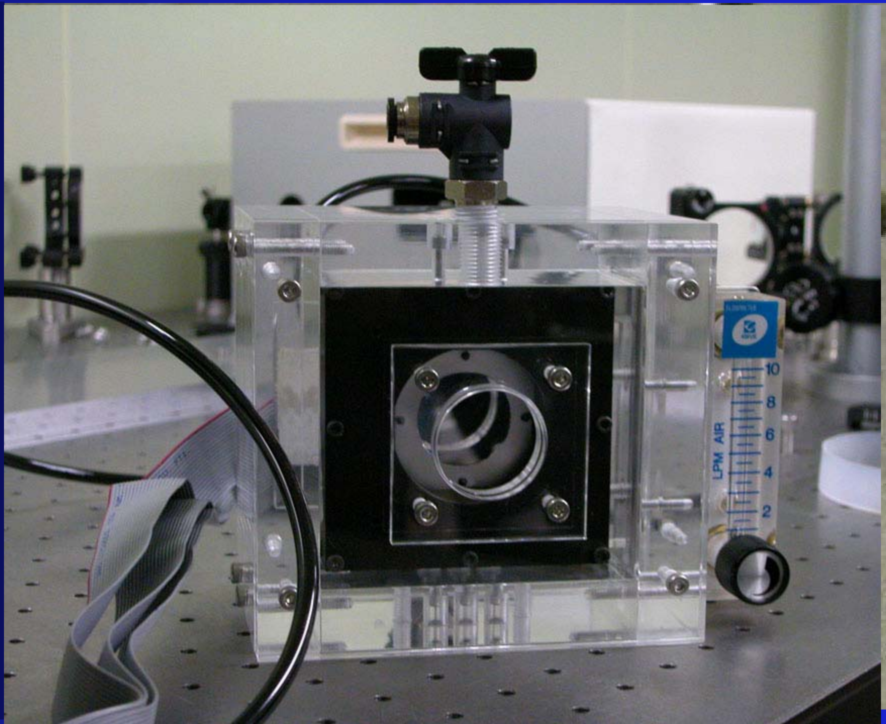
→ **Necessity of special algorithm to optimize**

Genetic + Neuron model Algorithm

- Al-coated SiN-Membrane
  (R > 70% in UV after 1 week)
- Hexagonal elements
  (59 channels)

Note that: Membrane is very delicate !!

We build dry N_2-Housing for DM.



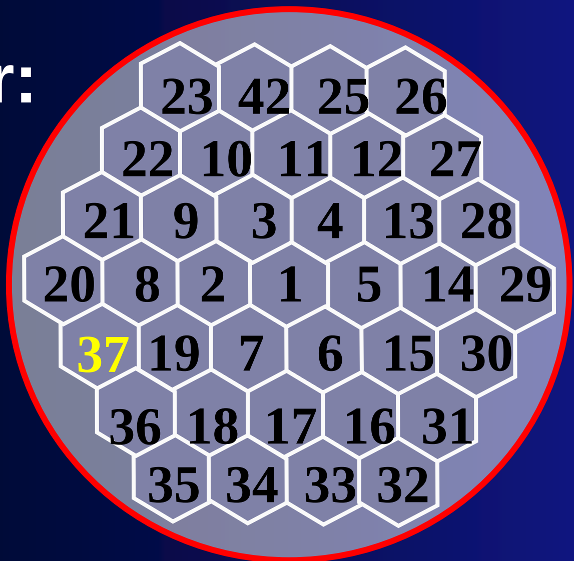
4-2. Spatial profile shaping with DM

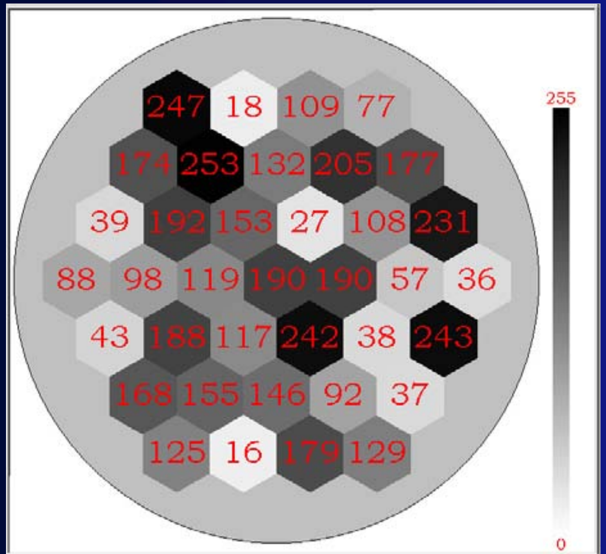
4-2-2. Deformable Mirror Actuator (ex. 37ch)

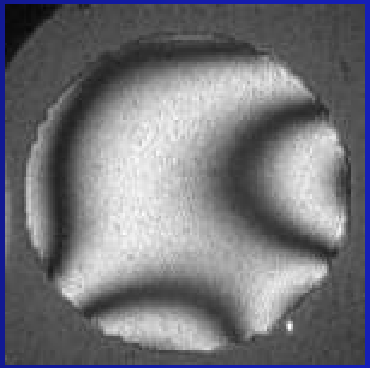
Voltage: 0 ~ 255 V

Probability: 256^{59} ~10^{141} for 59ch (in our case)

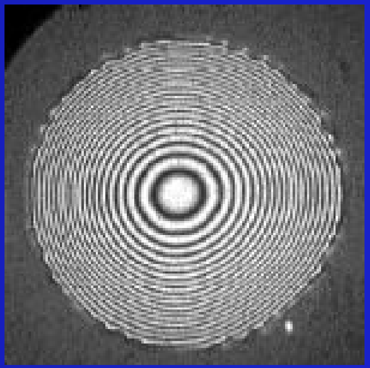
Actuator:



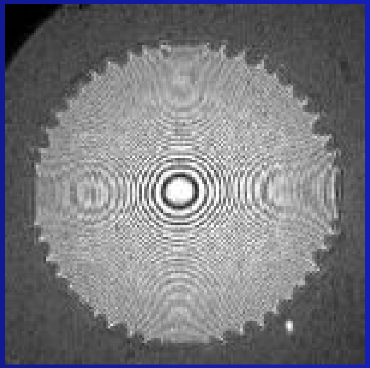




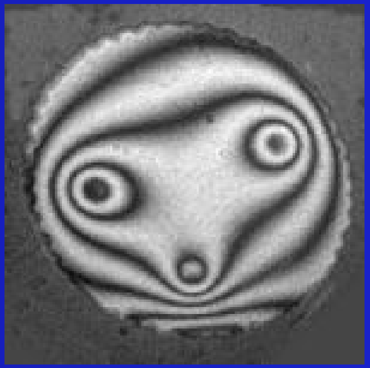
Initial State (All: 0V)



All: 125V



All: 255V (Max. Voltage)



Random Voltage

4-2. Spatial profile shaping with DM

4-2-3. Automation of optimization

Genetic Algorithm (GA) ~ Idea of Evolution ~

Genetic Algorithm

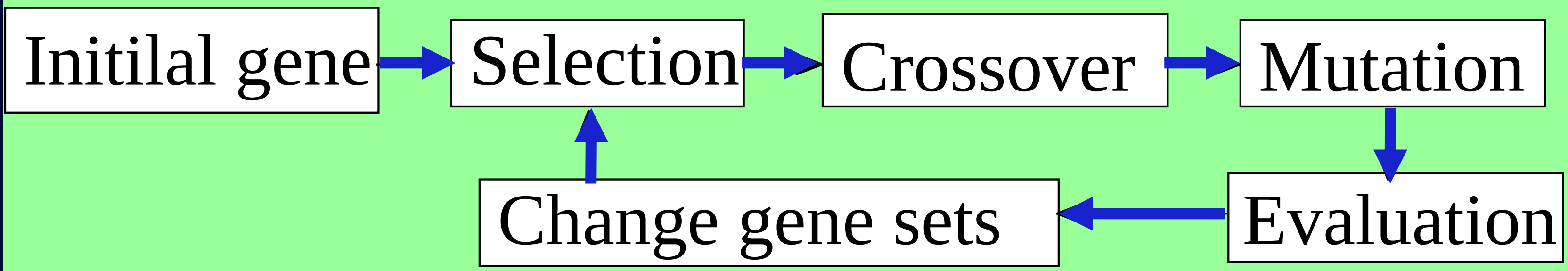
<Basic Process>

1) **Coding** : Digitize control parameters

gene							
1	0	1	1	1	0	0	0

2) **Initialization** : prepare a sets of gene

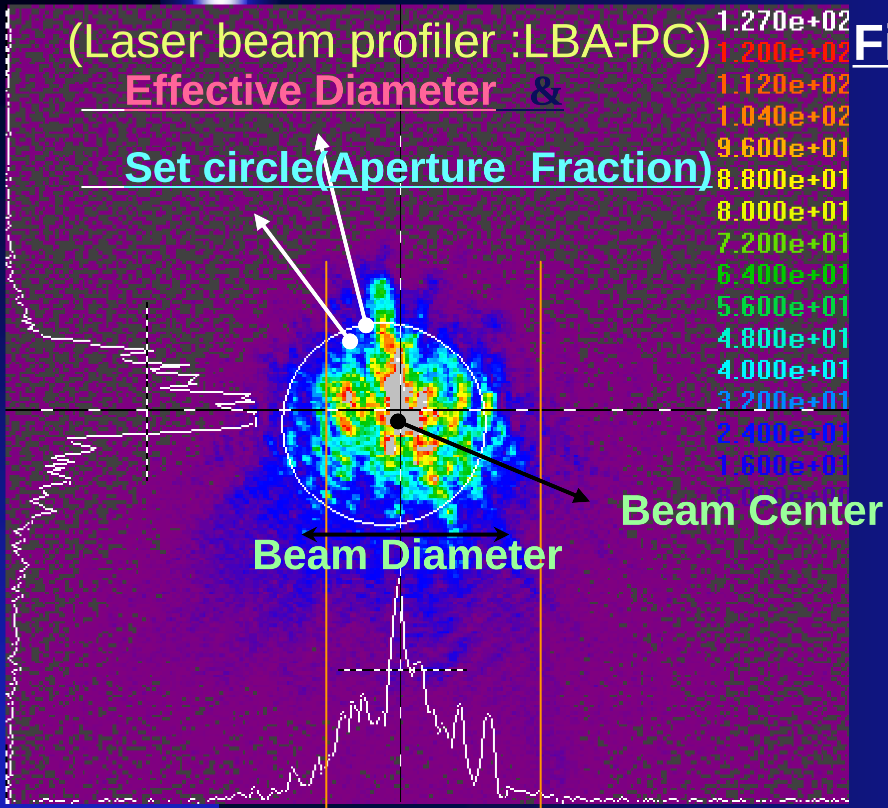
3) Basic Process

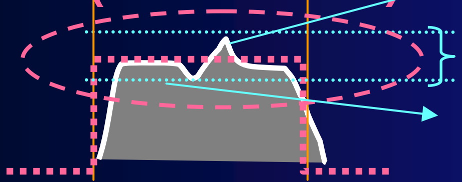


Fitting Function to evaluate Flattop profiles

Laser profile during optimization

(Laser beam profiler :LBA-PC)





Intensity distribution (cross section)

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

$$f(\textit{profiles}) = a + b + c + d + e + f + g + h + i$$

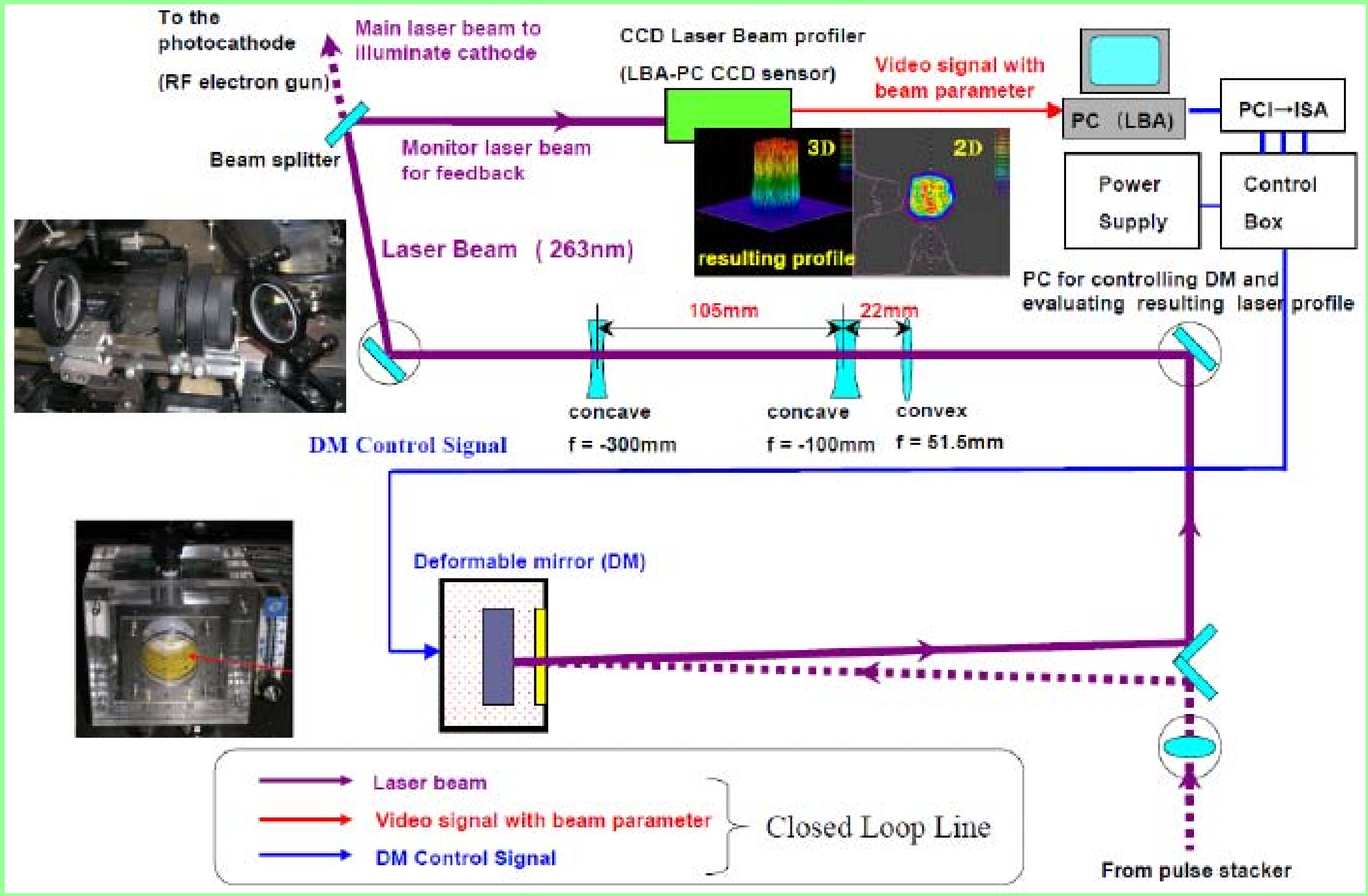
1. **Top Hat Factor**: Maximize the Top Hat Factor (0 ~ 1)
2. **Effective Diameter**: Minimize the difference between the diameters of set circle and measured
3. **Flatness (Std Dev/mean)**: Minimize the standard deviation divided by the average in a flattop area
4. **Aperture Fraction**: Maximize the 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

Weight of each term of fitting function for *Flattop*

~ decided by comparing convergence status ~

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

Closed Control System for experiment



4-2. Spatial profile shaping with DM

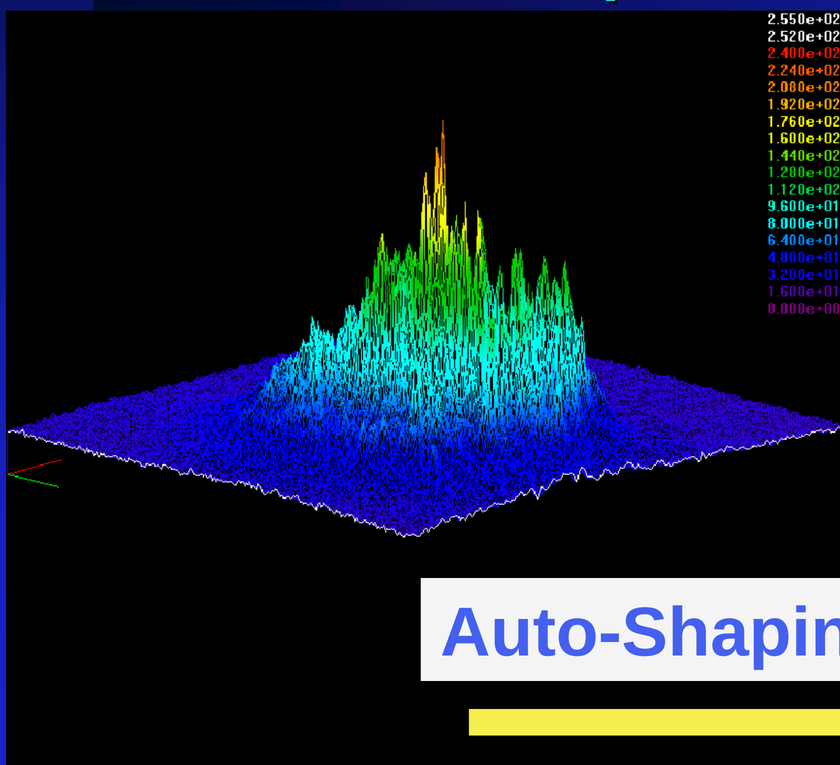
4-2-4. Results of the combination DM GA

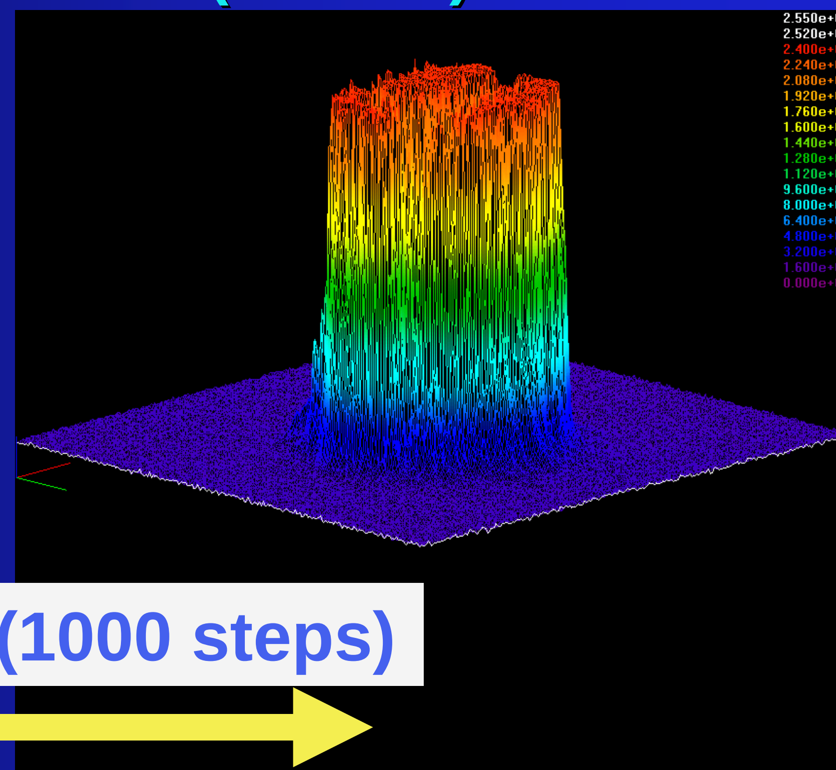
This shaping with computer-aided **DM** was done @THG

⇨ **Flattop shaping OK!**

Computer-aided **DM** for UV (THG)

⇨ **No problem for FHG (197 nm)**



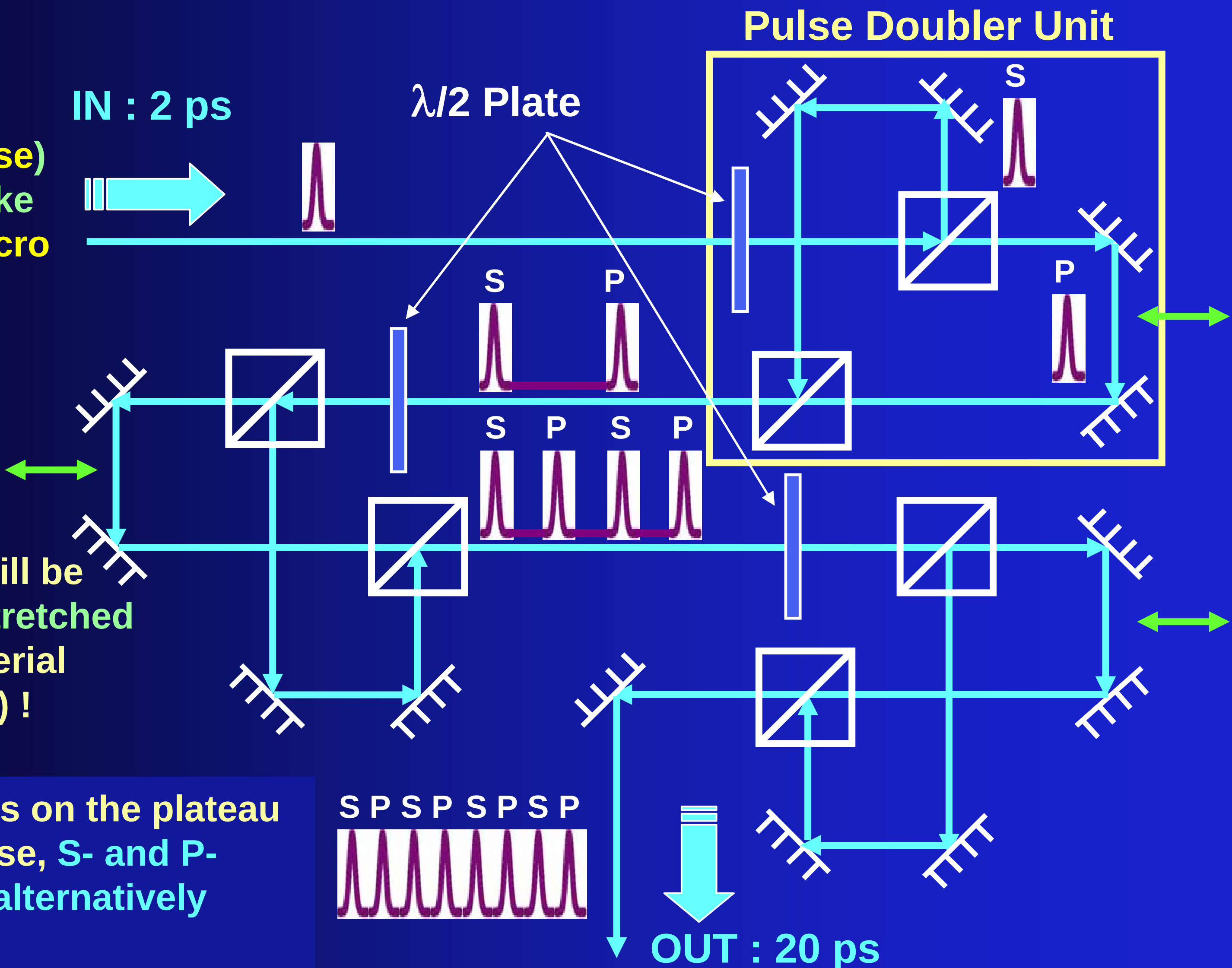


Auto-Shaping (1000 steps)

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!



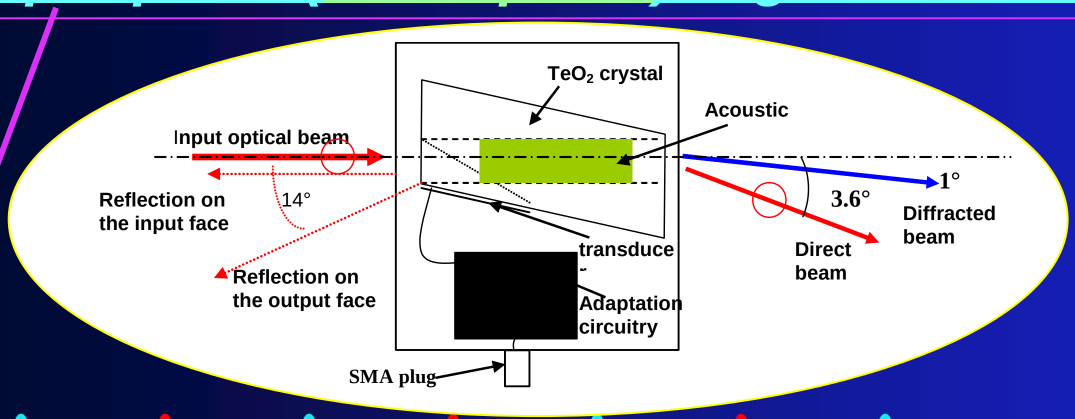
Not that, laser pulse will be positively chirped & stretched through the silica material (laser transport optics) !

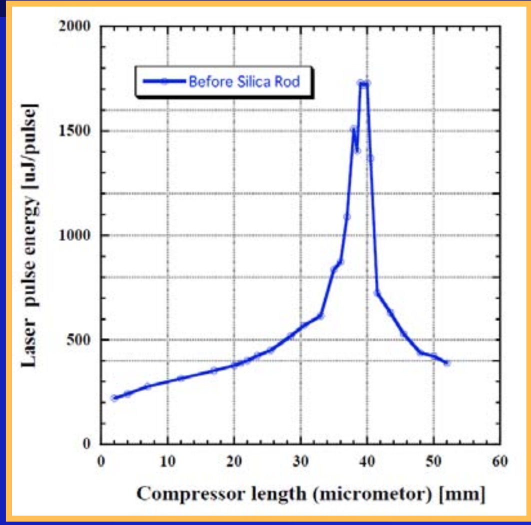
To avoid interferences on the plateau of stacked macro pulse, S- and P-polarized pulses are alternatively positioned!

4-3. Temporal profile shaping (Pulse stacking)

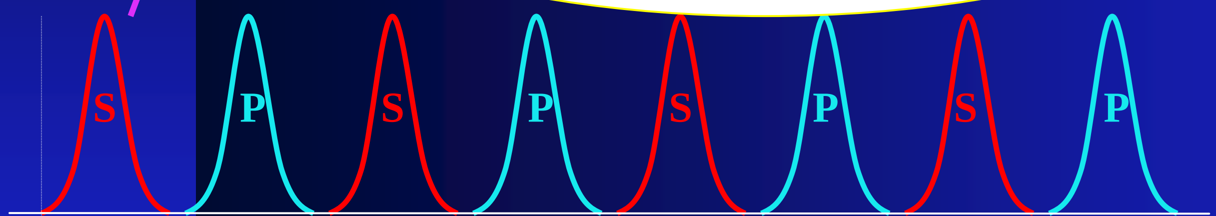
4-3-2. Input pulse optimized with AO-modulator

Changing 2nd dispersion with AO (DAZZLER),
2.5-ps input pulse (micro pulse) is generated





Positive ⇦ ⇨ Negative



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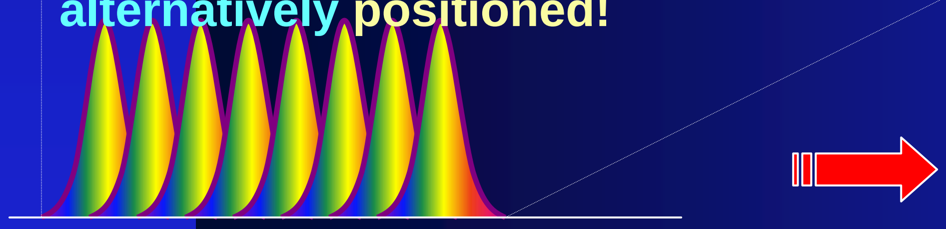
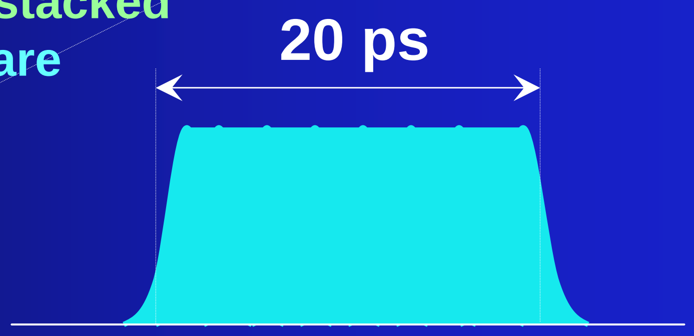
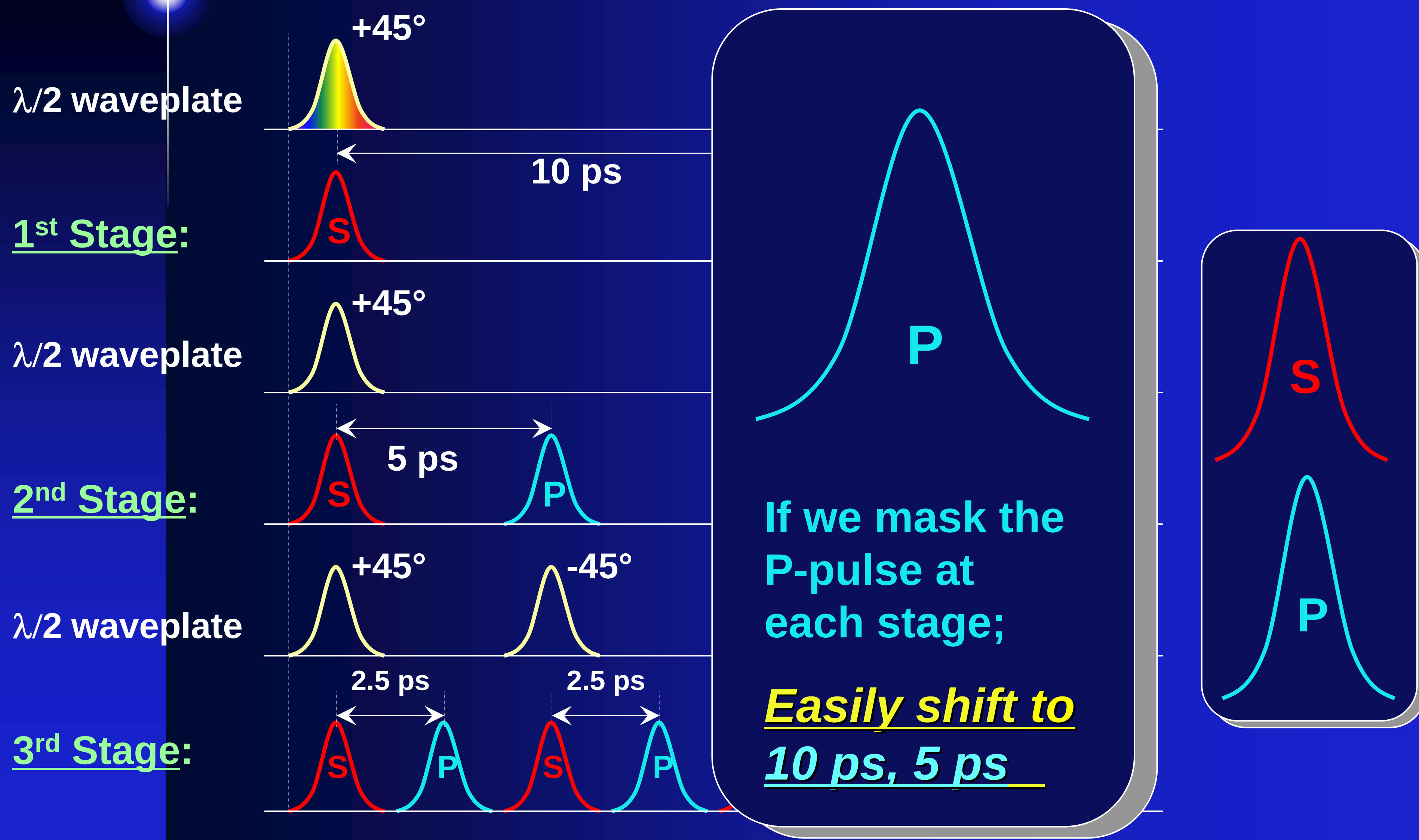




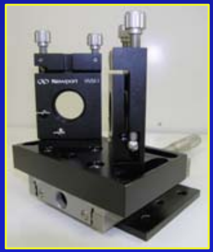
Time chart of pulse stacking:

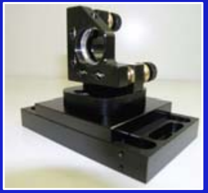
3 stages for generation of 20 ps square macro pulse

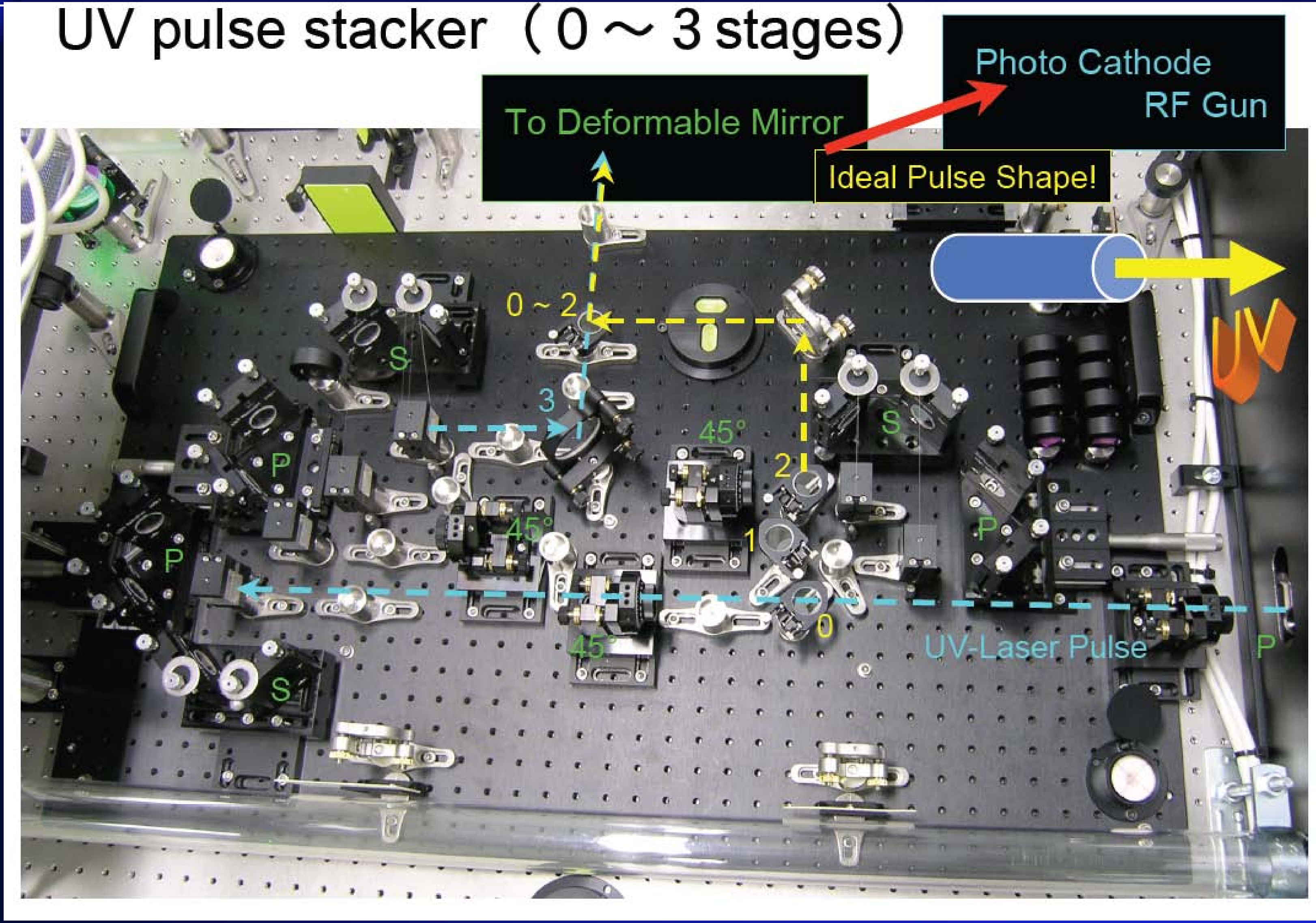


4-3. Temporal profile shaping (Pulse stacking)

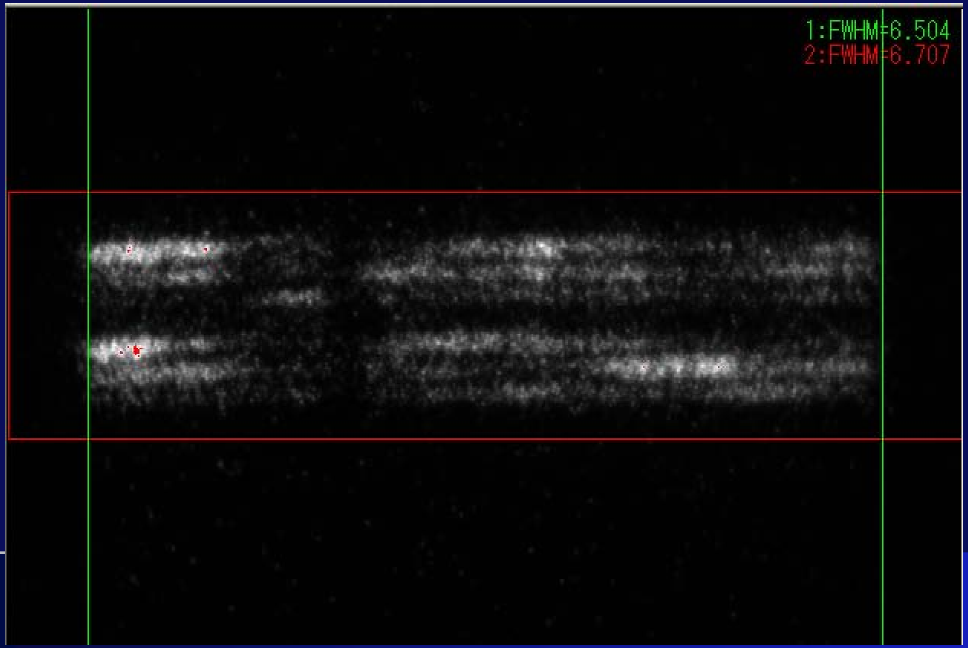
4-3-3. Developed UV-Pulse Stacker

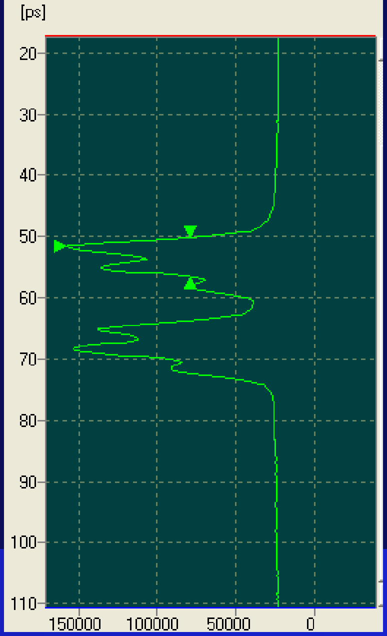






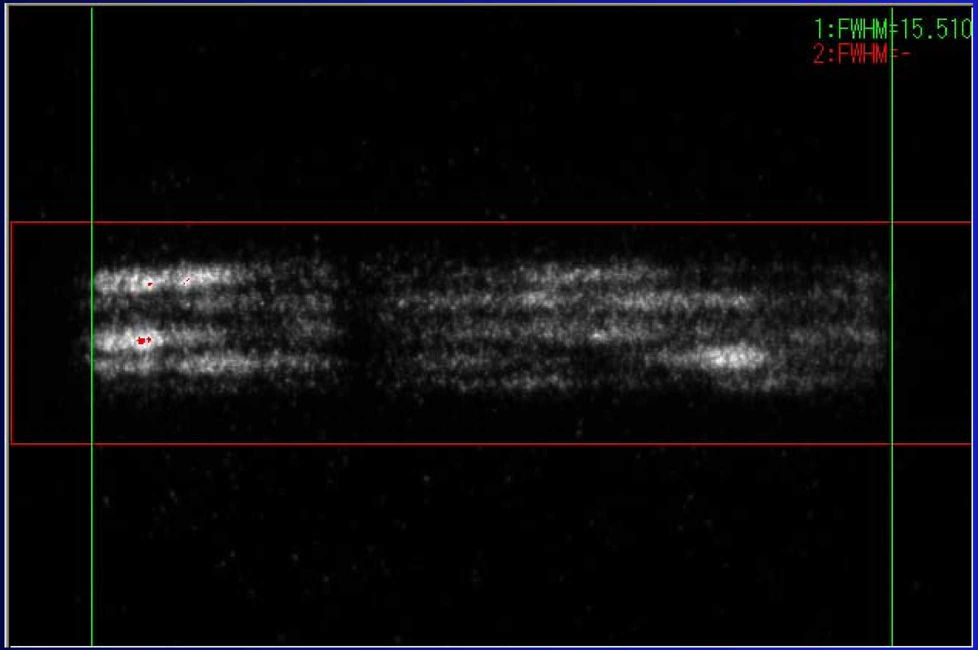
Two 6.5-ps stacked sub-macro stricture
14 ps between them

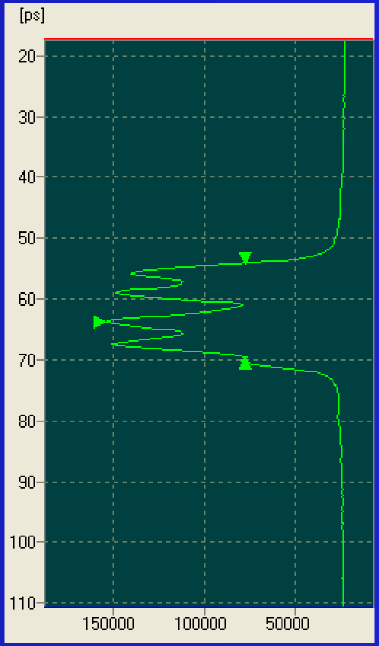




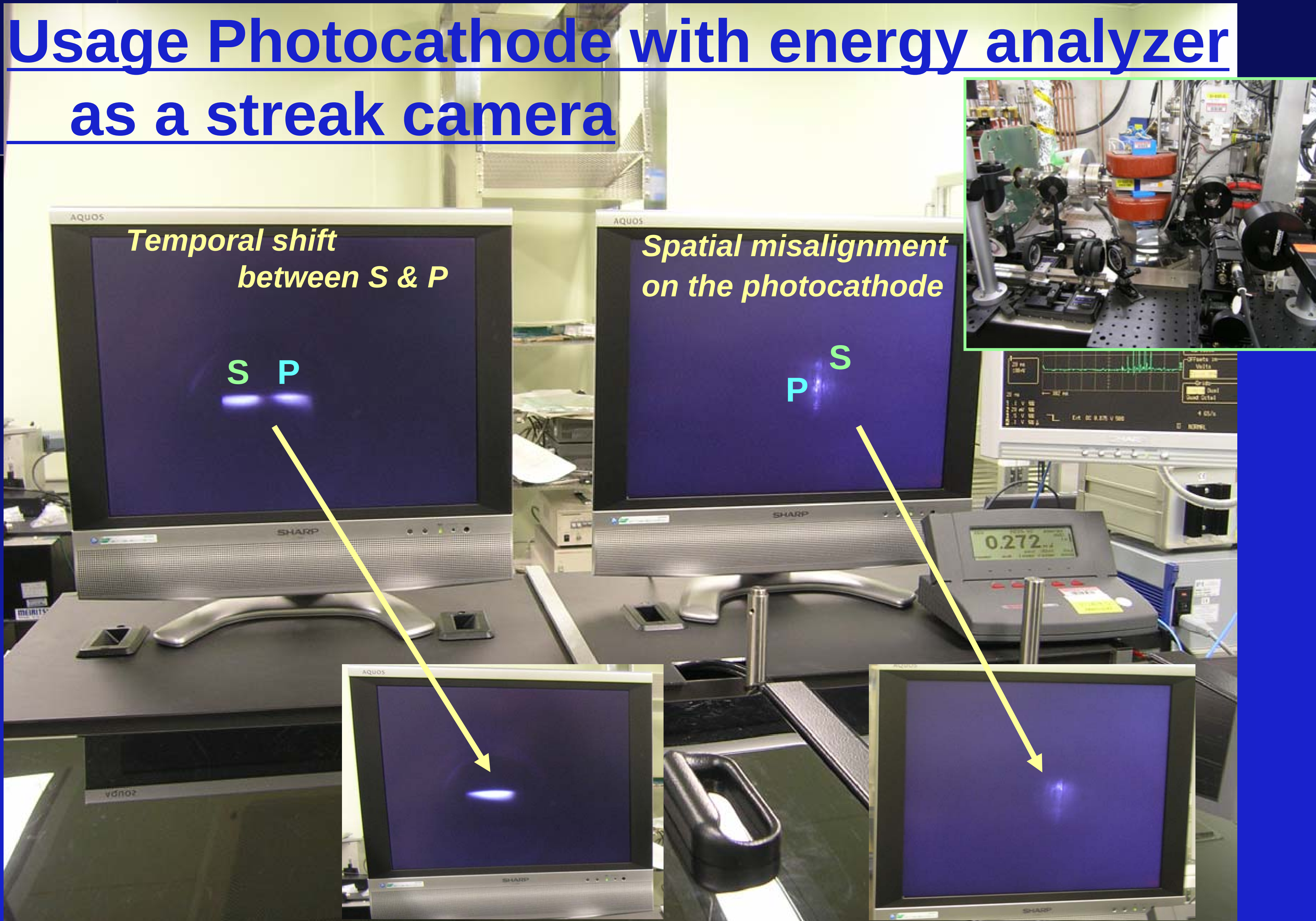
Shifting optical delay 1

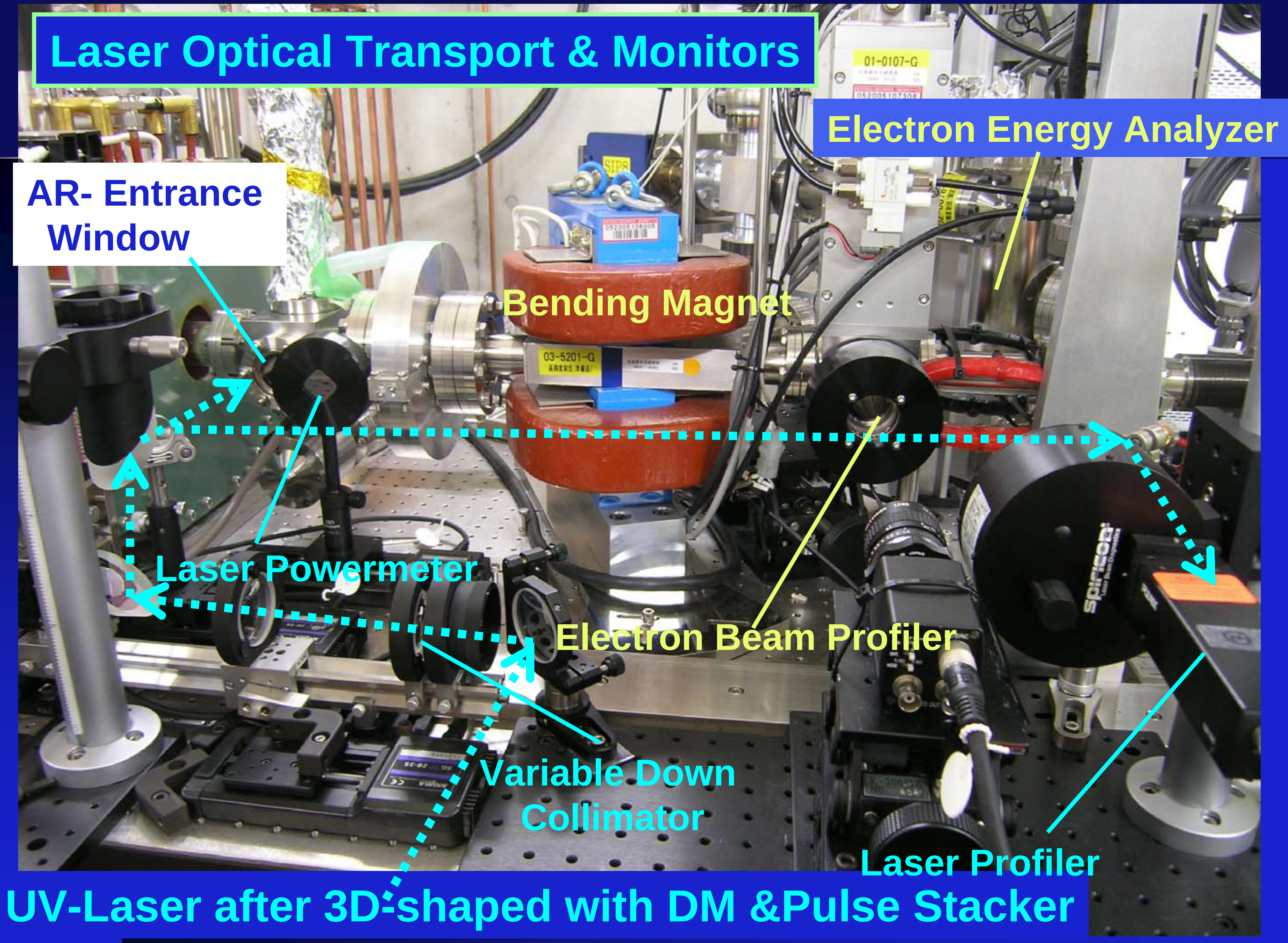
All stacked together
15.5 ps FWHM



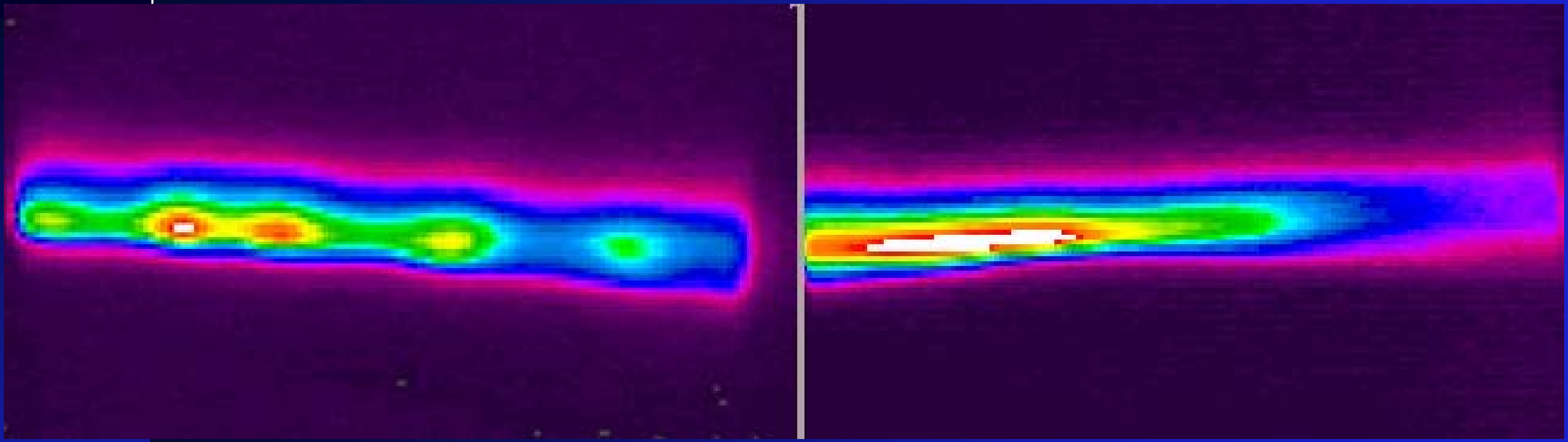


Usage Photocathode with energy analyzer as a streak camera




Laser Optical Transport & Monitors
Electron Energy Analyzer
AR- Entrance Window
Bending Magnet
Laser Powermeter
Electron Beam Profiler
Variable Down Collimator
Laser Profiler
UV-Laser after 3D-shaped with DM &Pulse Stacker

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!

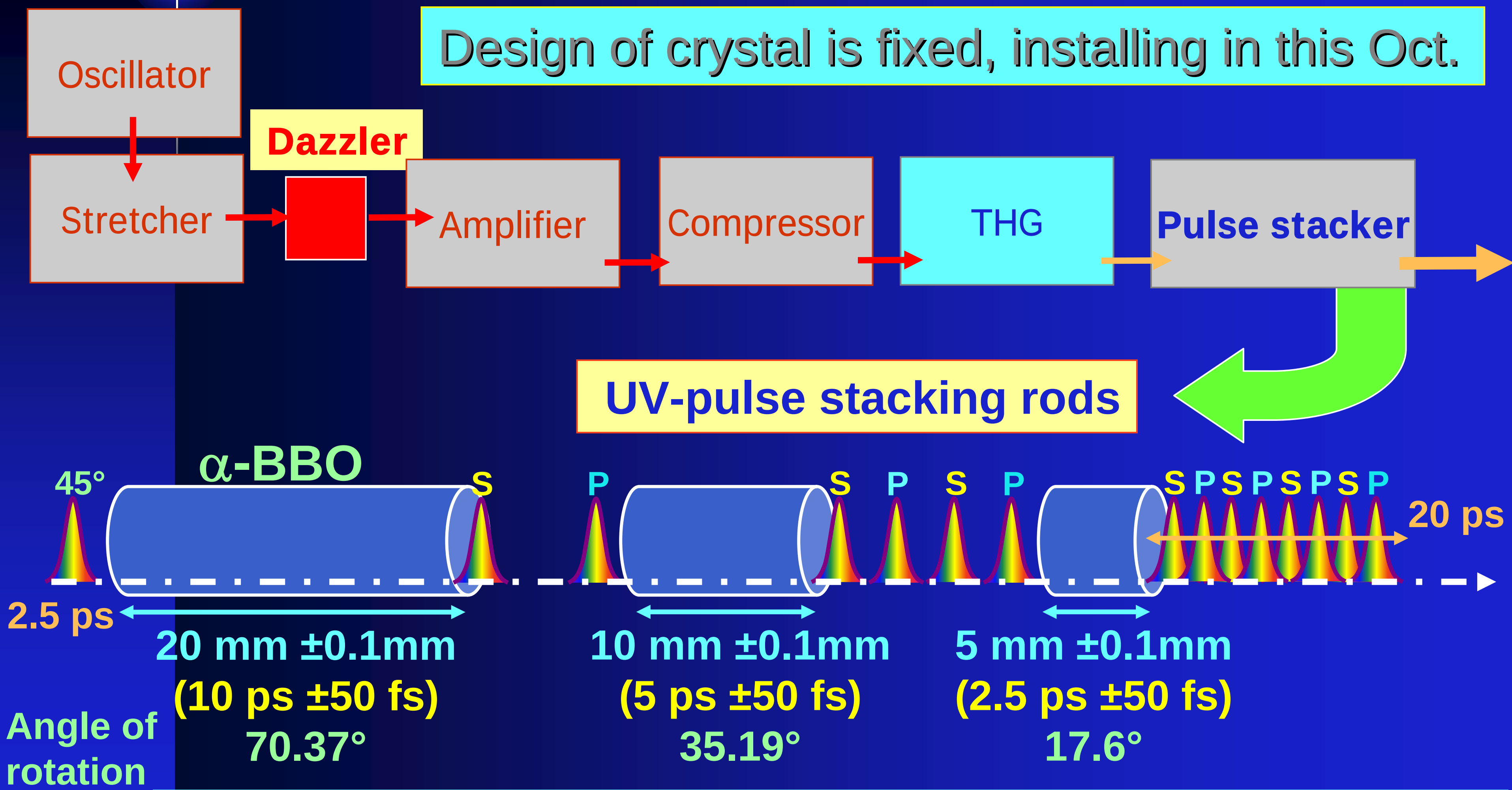
Stacked Pulse Duration: 20 ps

(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



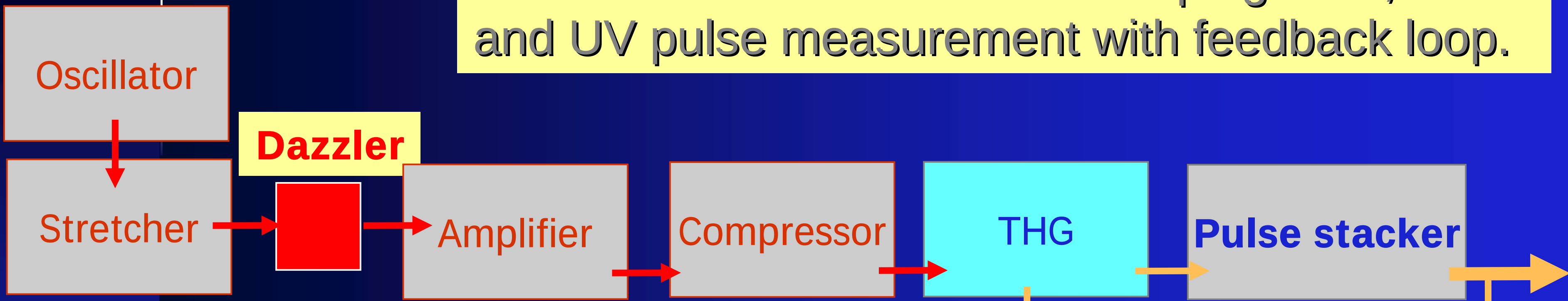
Optical Rotatory Dispersion (ORD); Kramers-Kronig relation

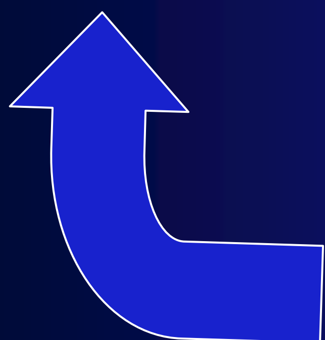
4-3. Temporal profile shaping (future planning)

4-3-5. Adaptive micro-pulse optimizing with 2 AO

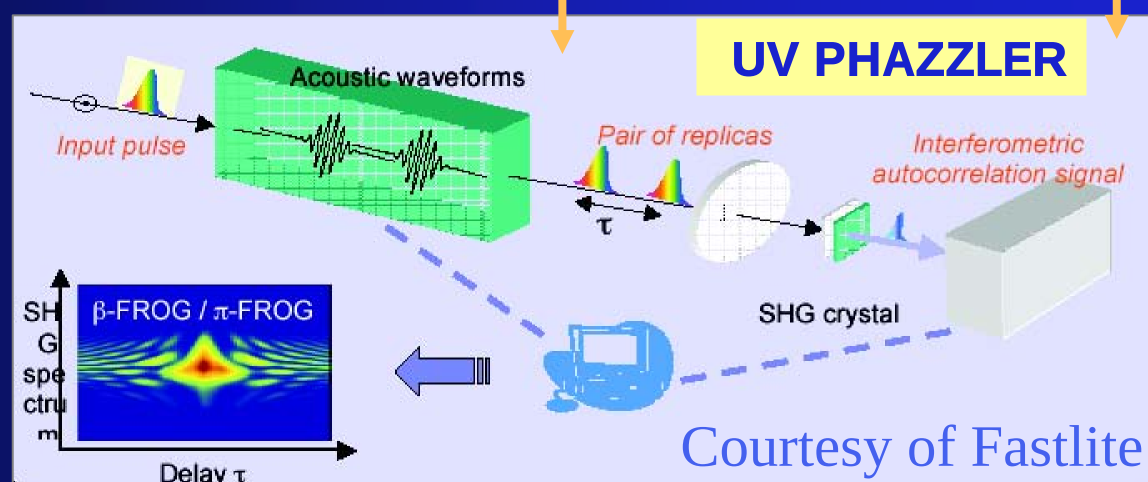
- UV- & IR-DAZZLER feedback sys.+ Pulse Stacker

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





Feedback loop will be done in 2008

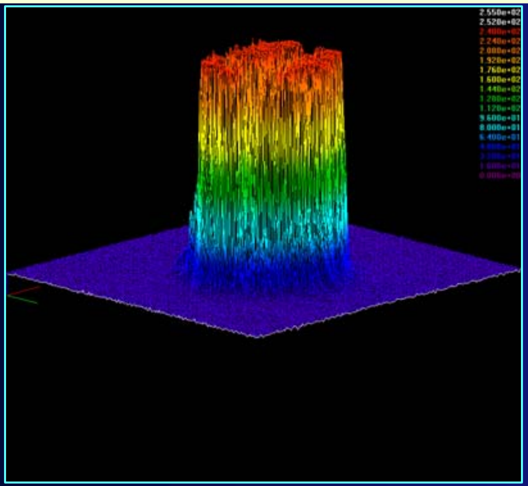


5. Emittance measurements

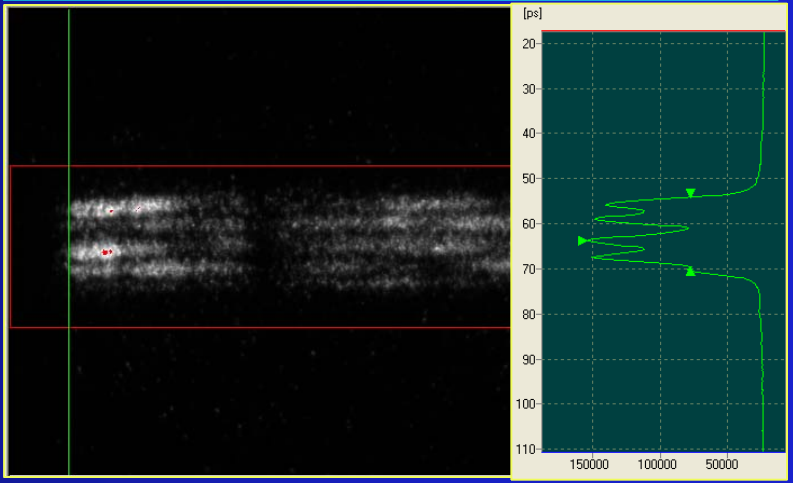
5-1. 3D- Laser Beam Shape for experiment

~ present status at SPring-8 ~

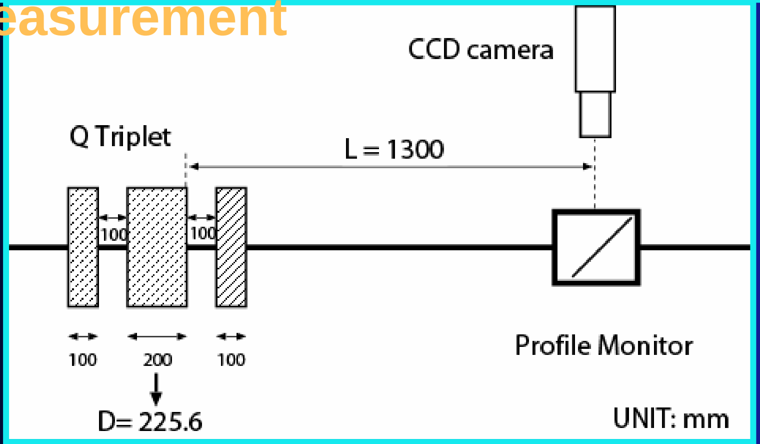
Flattop : φ0.8 mm

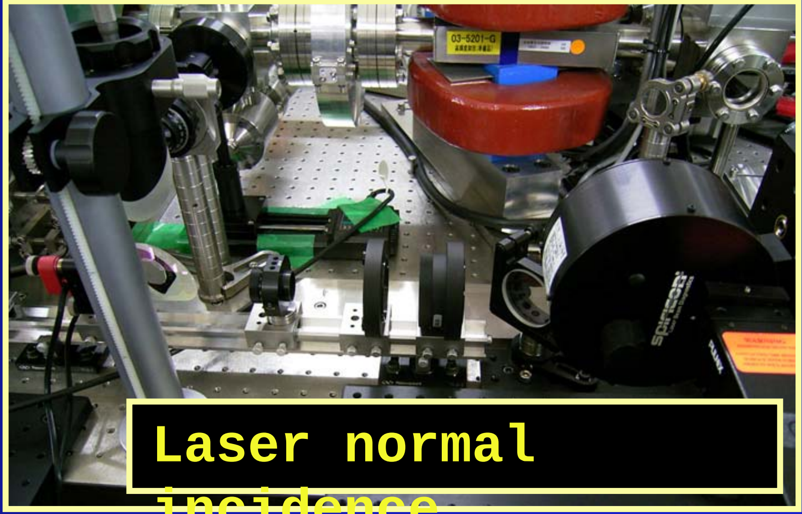


Square pulse 20 ps



Q-scan emittance measurement





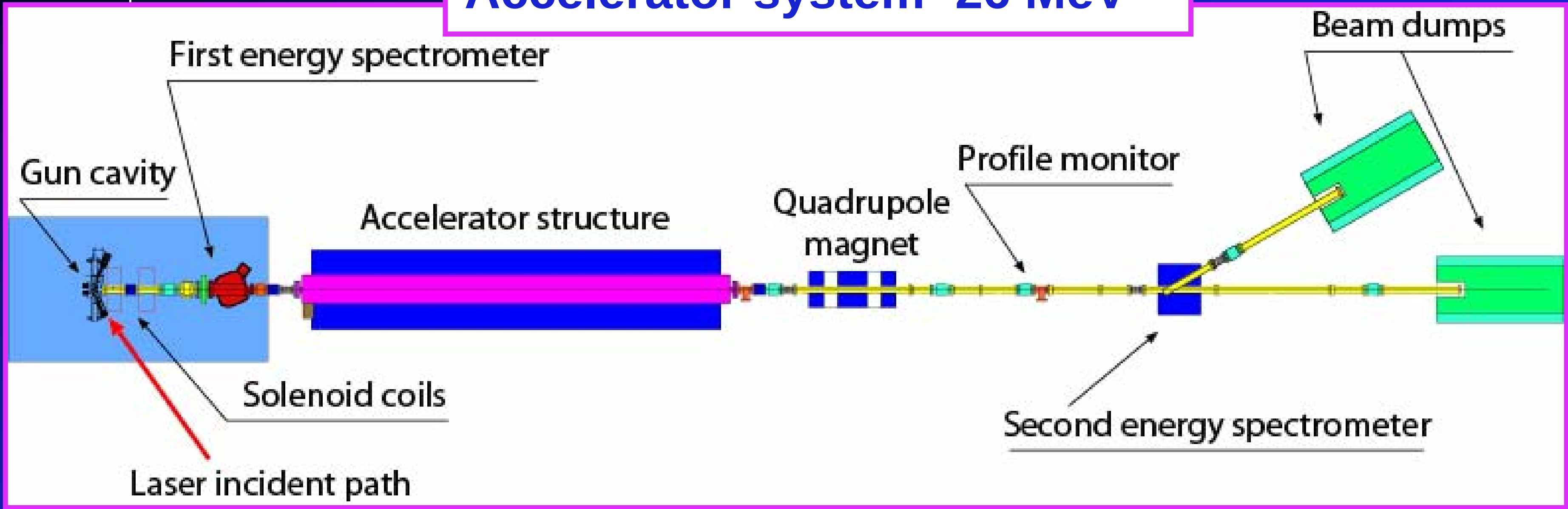
Laser normal incidence

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: 2.0π mm mrad 1.0 nC

Stacked pulse duration 20 p

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 ~

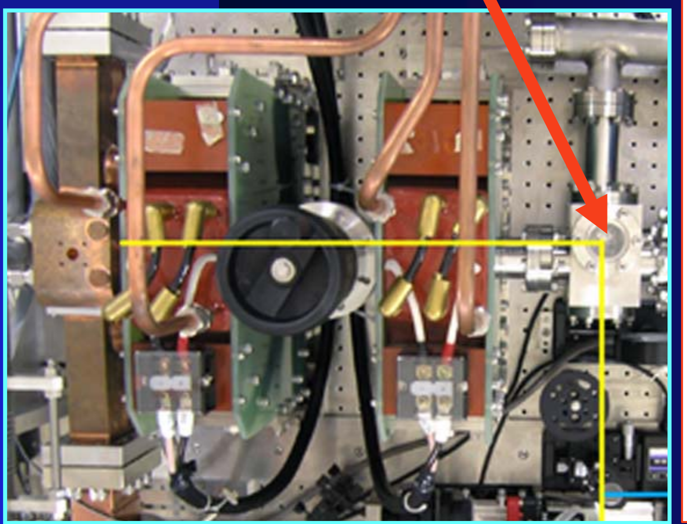
Result of emittance measurement: **2.0π mm mrad @1.0 nC**

Pulse duration 20 ps

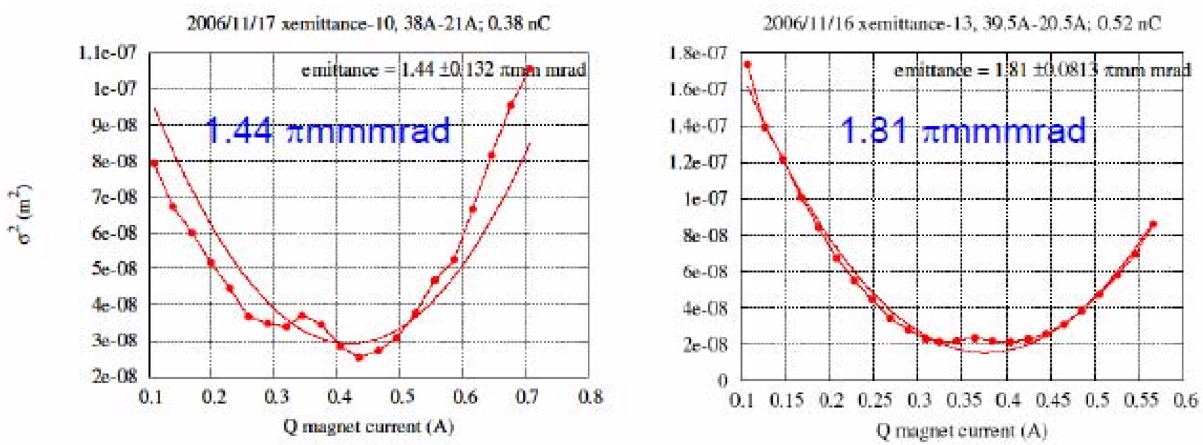
Some space charge limitation ? **1.8π mm mrad @ 0.5 nC; 15 ps**

1.4π mm mrad @ 0.4 nC; 10 ps

Normal incident mirror ?



Q-scan fitting



10 ps, 0.38 nC

15 ps, 0.52 nC

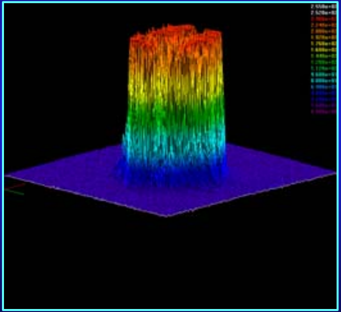
6. Summary & future plan

~ stable & qualified beam ~

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

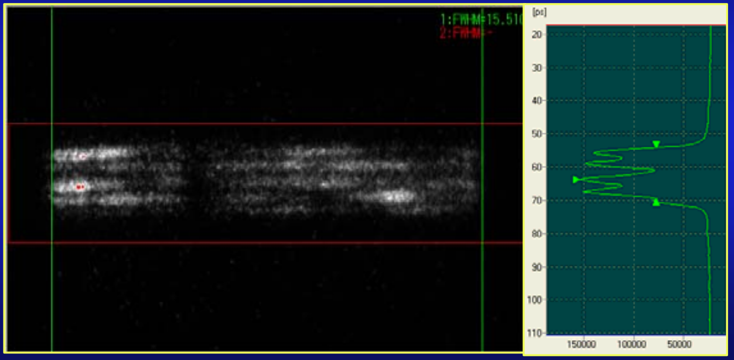
B. Automatically shaping Spatial Profile with DM + GA was successful! (Gaussian or Flattop)



~ Arbitrary Laser Shaping ~

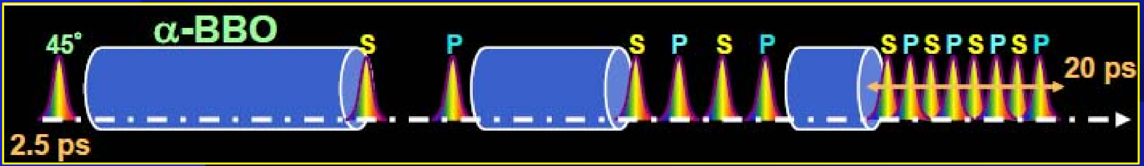
~ However, it takes 1 hour to optimize.

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

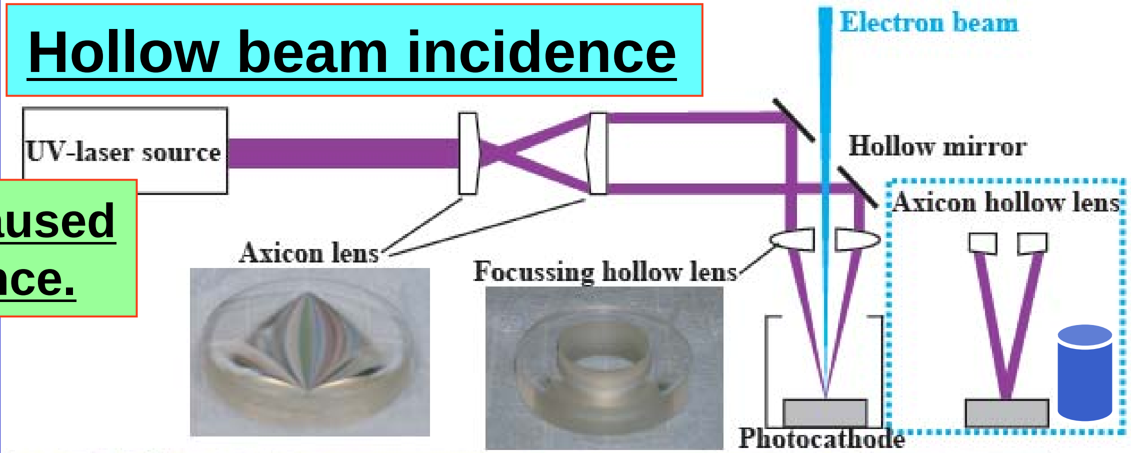
2.0π mm mrad @1.0 nC; 20 ps

1.8π mm mrad @ 0.5 nC; 15 ps

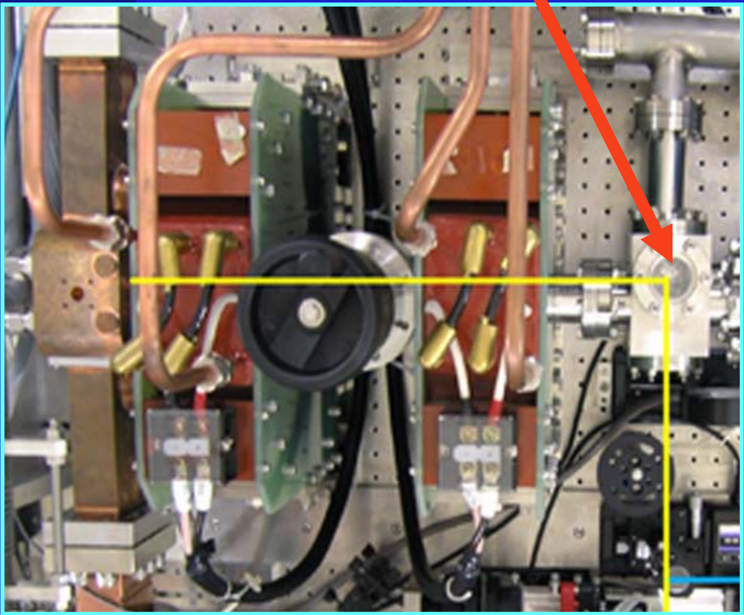
1.4π mm mrad @ 0.4 nC; 10 ps

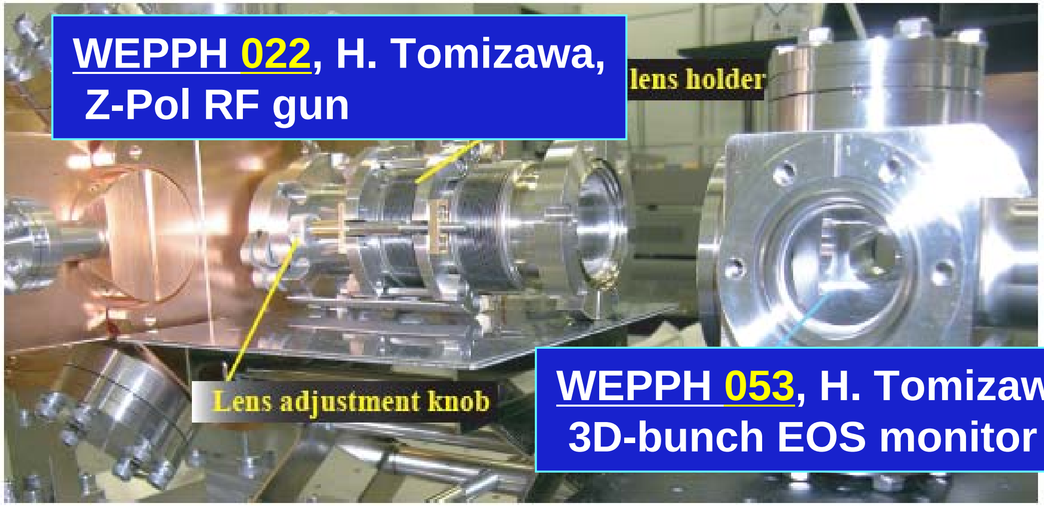
E. New incidence system

Hollow beam incidence



Normal incident mirror can be caused of difference bw X- and y-emittance.





WEPPH 022, H. Tomizawa, Z-Pol RF gun

WEPPH 053, H. Tomizawa, 3D-bunch EOS monitor

Wk h#hqg

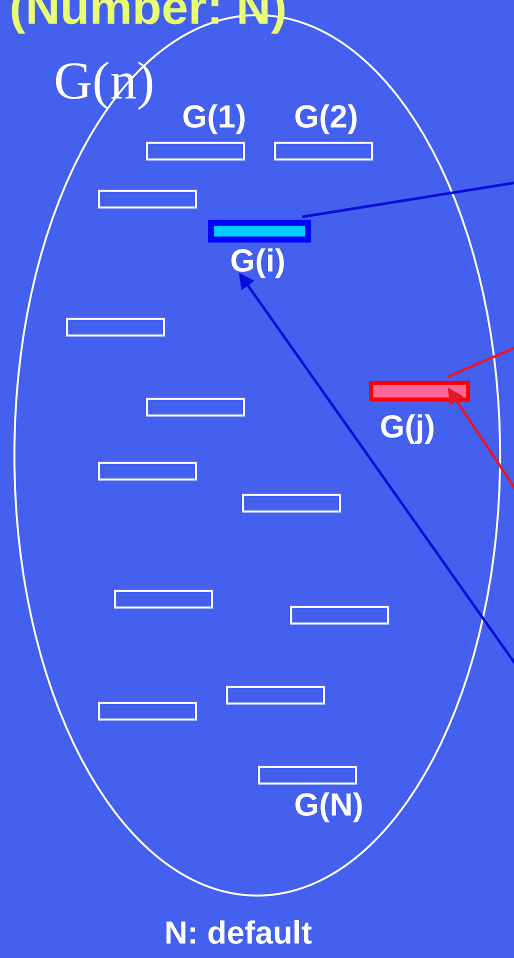
DAZZLER AO-Modulator (micro pulse shaper)

+ Fundamental => THG (micro) pulse

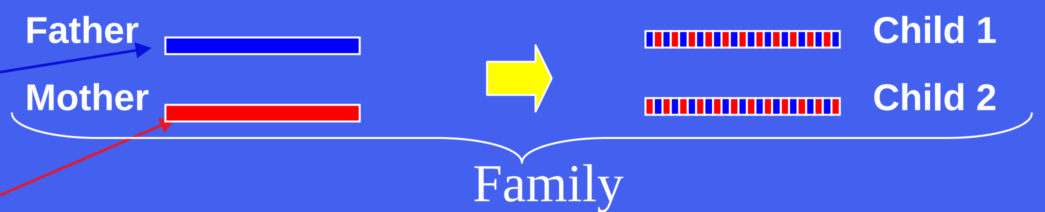
Summary of Fiber Bundle Shaping

- 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.

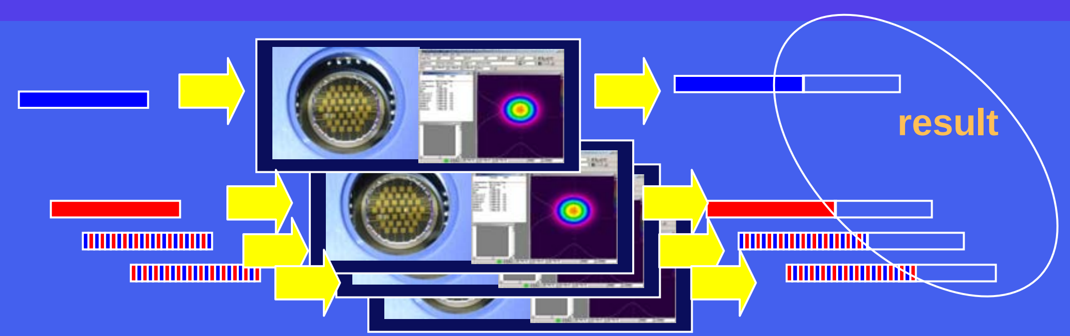
Procedure (1 step): MGG (Minimal Generation Gap)



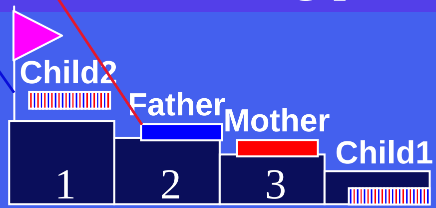
(1) Random select Parents and generate Children (Family)



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



(3) Evaluate resulting parameter (Close to Flattop)



Resulted new order of priority

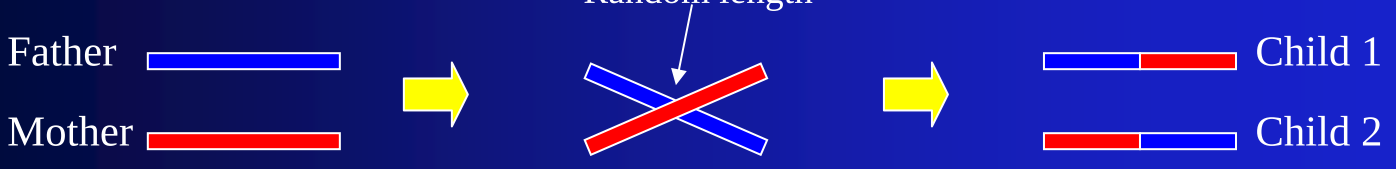
Child2 > Father > Mother > Child1

Selected!

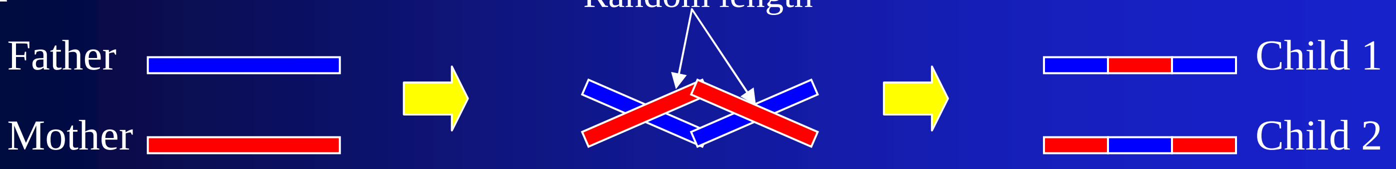
(4) The best two Chromosomes (Next Parents (i),(j))

How to create gene of child? (Crossover)

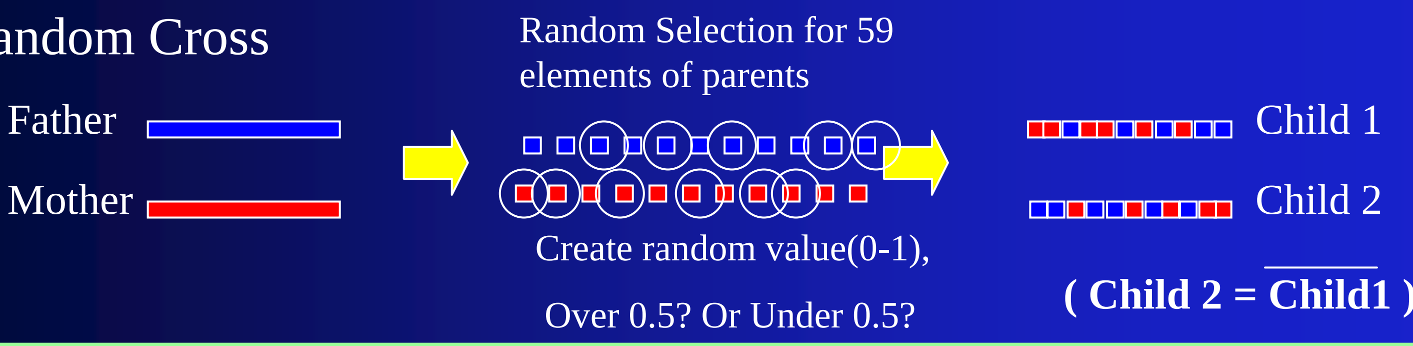
(1) 1 point Cross



(2) 2 point Cross



(3) Random Cross



The reason to chose   simple to program