Laser 3D-shaping Experiment

~ toward to electron bunch shaping ~

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1. Introduction ~ Present status of UV-laser source @SP8 ~
2. Motivation for beam quality control
3. Optimization system of spatial profile
   - Automation with DM + Genetic Algorithms
4. Optimization system of temporal profile
   - UV-Pulse Stacker
   - Automation with Silica-SLM + SA
5. Summary and future plan (Appendix)

1. Introduction

1-1. Highly qualified Laser light source

1. For generation of the lower emittance beam
   → Optimization of laser 3D-profiles (Spatial & Temporal)

2. For a lower jitter system
   → Stabilization of laser oscillator (seeding)
   through environmental control

3. For a long-term stabilization of Laser Output & higher pointing stability
   → Stabilization of total laser system
   through environmental control

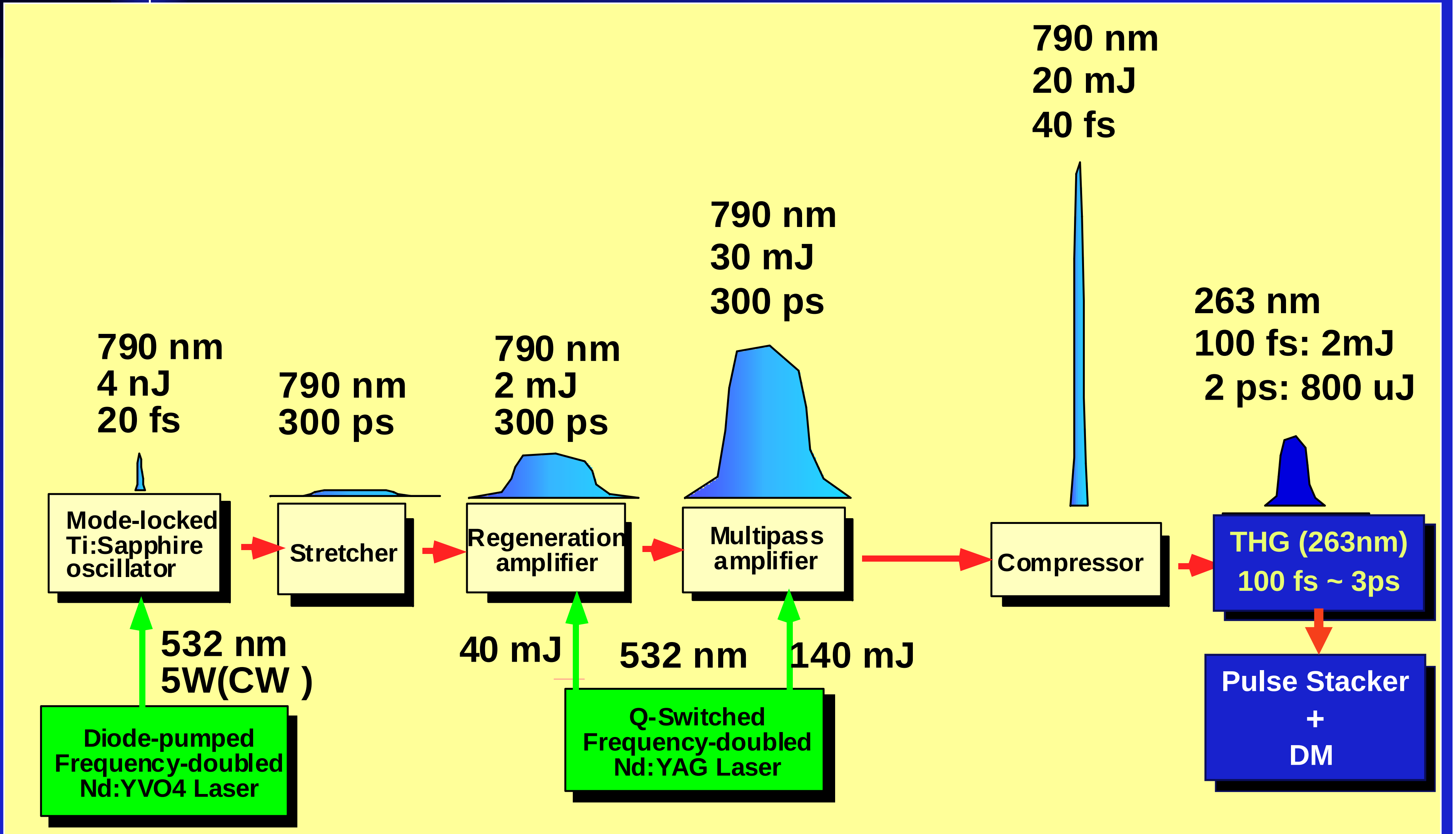
In principle,
Environmental control!

Note that, passive stabilization is the most important for beam quality control !

1. Introduction

1-2. Ti:Sa Laser System Configuration

~ Femto second TW- Ti:Sa Laser System ~

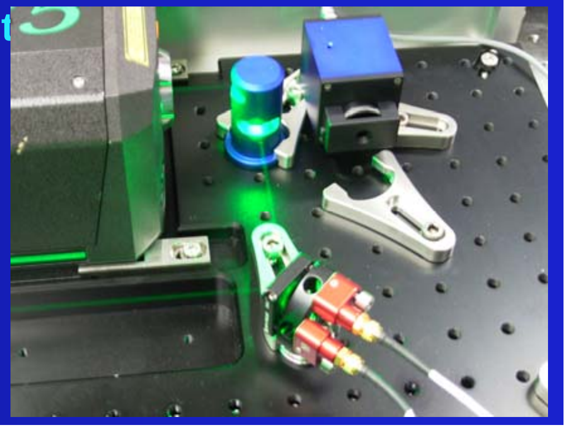


1. Introduction

1-3. Present status of Laser System in humidity (55%) -controlled clean room

Laser System
after passive stabilization
with Temperature-control Plate

New Oscillator with auto alignment

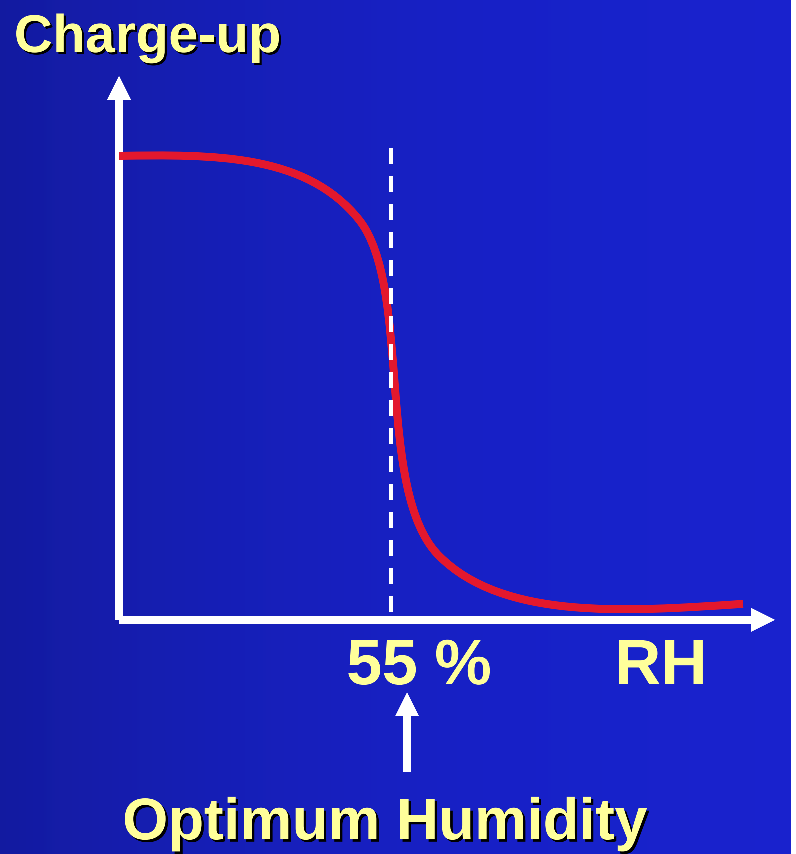


Humidification for avoiding charge-up

Environmental test clean room

Hum
(pur

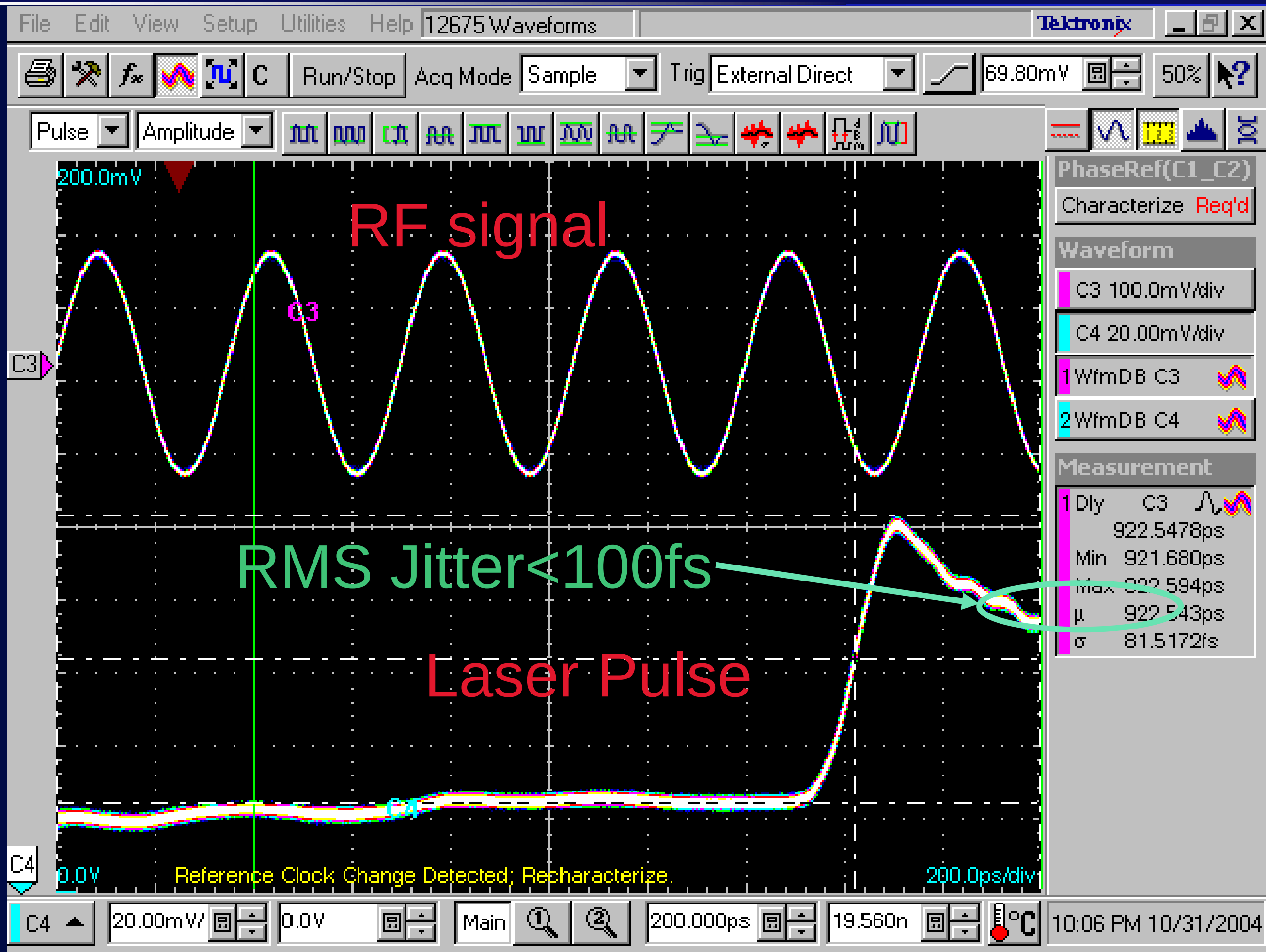
Constant Temperature & Humidity



(Under Construction and Laser Replacement: 2002 ~2004)

1. Introduction

1-4. Laser & RF Synchronization



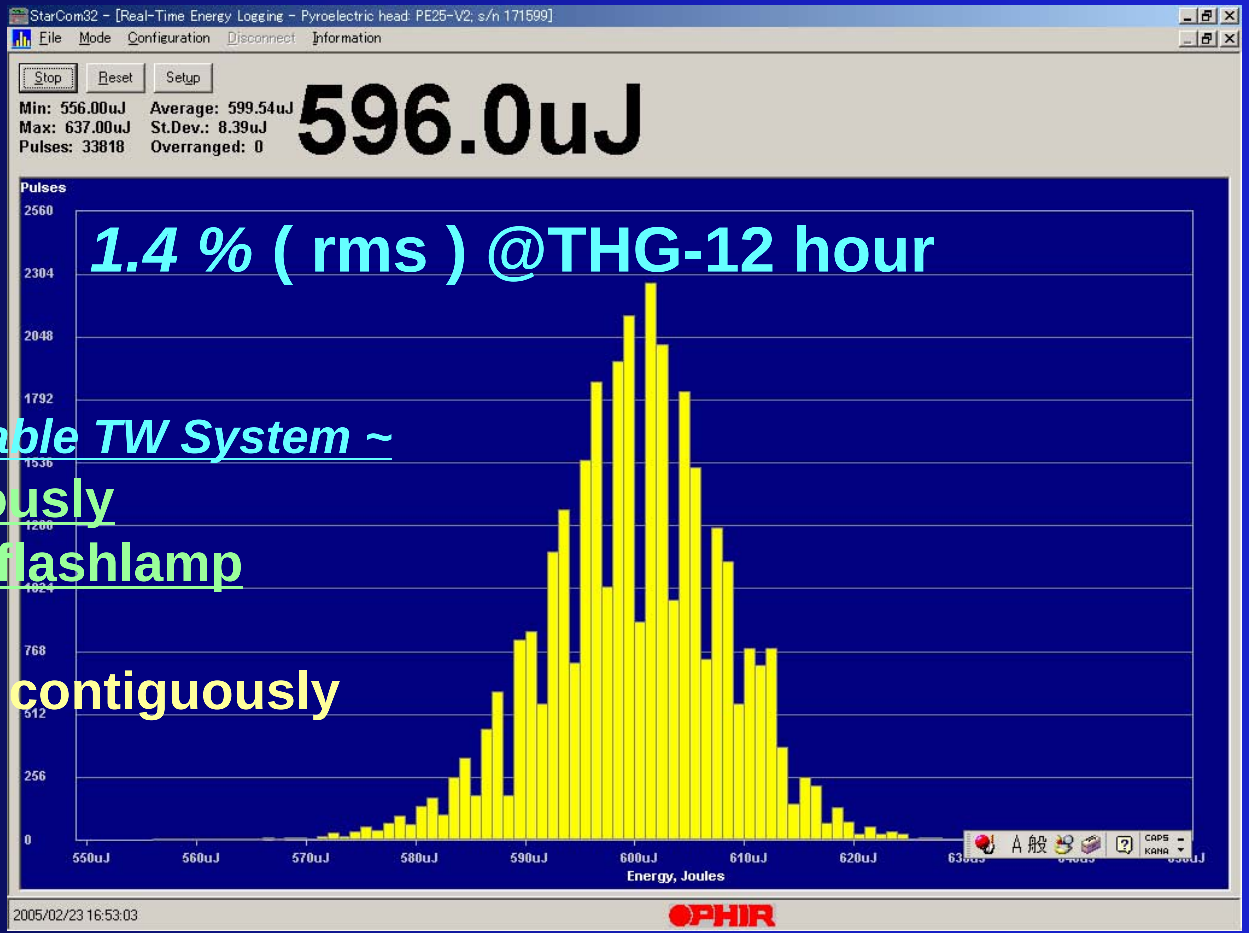
Time delay between RF signal & Laser pulse measured with Tektronix TDS8200 Sampling Oscilloscope

1. Introduction

1-5. The present status of stability of UV-Laser

Present stability:

0.2 ~ 0.3 % **(rms)**
@ Fundamental



***1.4 %* (rms) @THG-12 hour**

Long Term: ***~ the most stable TW System ~***

4 – 5 Weeks continuously
limited by lifetime of flashlamp

New Oscillator has been contiguously operated *last 4 months.*

After Passive control

***5 ~ 10 %* (rms) → *0.95 ~ 1.4 %* (rms)**

2. Motivation for beam quality control

2-1. Physical background of ideal laser profile

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

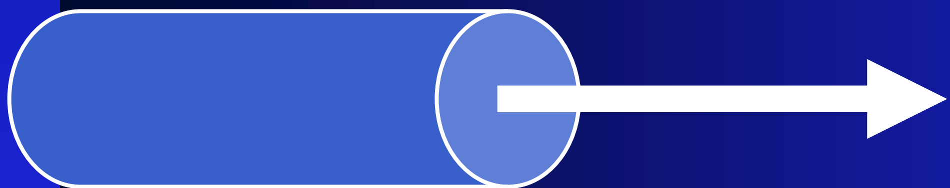
Space charge effect consists of:

1. **Linear term in radial direction**

   → **possible to compensate with Solenoid Coils**

2. **Non-linear term in radial direction**

   → **possible to suppress non-linear effects with optimization of ideal Laser Profile**



Note that, in real case ideal 3D-shape can be different!

Ellipsoidal ?

2. Motivation for beam quality control

2-2. 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

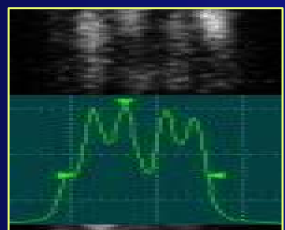
UV- Pulse Stacker

Pulse duration: 2.5 ps

Pulse duration: 10 ps

10 pps

Pulse Stacker



Streak Image of stacked pulses

Spatial Profile:

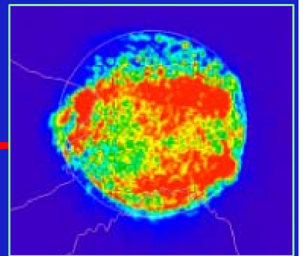
Distribution: Flattop

Deformable Mirror

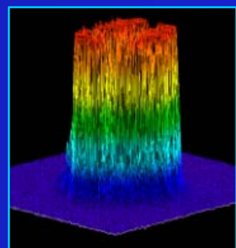
Gaussian

Diameter : 1 mm

Deformable Mirror



Flattop



2. Motivation for beam quality control

2-3. Automatic Laser Beam Quality control system

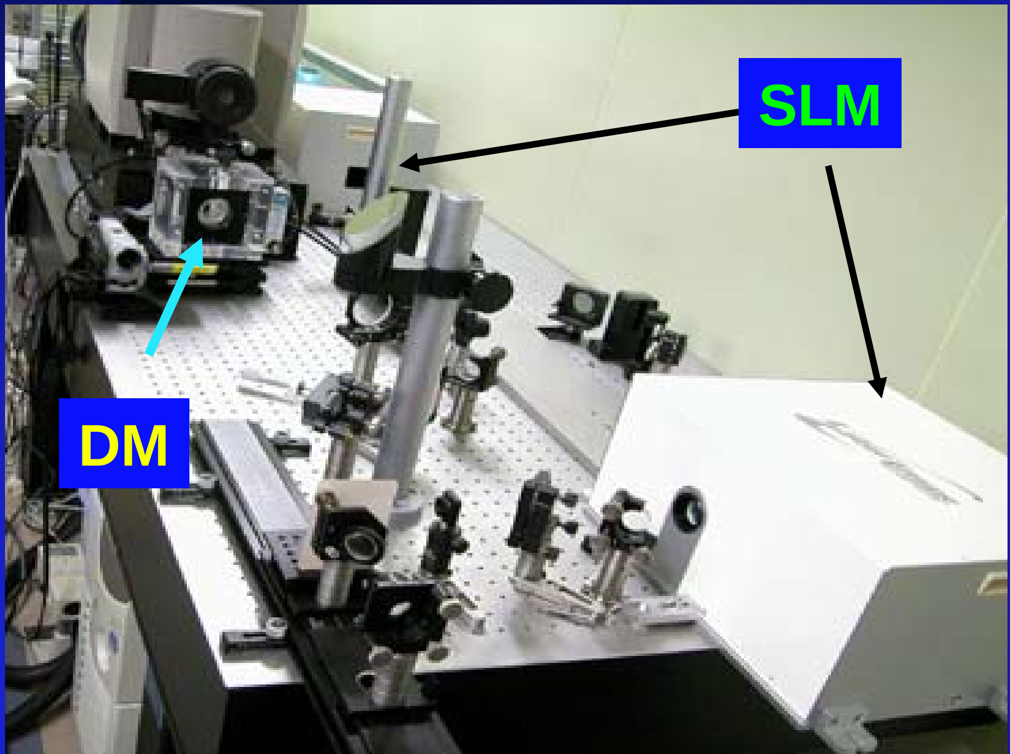
~ Arbitrary Laser Pulse Shaping ~

A) Computer-aided **SLM (Spatial Light Modulator)**

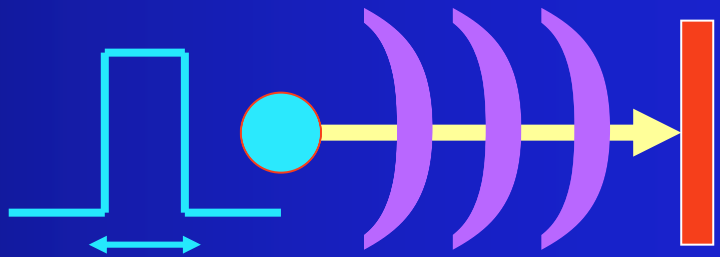
→ **Rectangular Pulse shaping (Arbitrary Shape)**

B) Computer-aided **DM (Deformable mirror)**

→ **Flattop spatial profile (Arbitrary Shape)**



Automatic Control Optics
- Spatial shaping (DM)
- Pulse shaping (SLM)
- Wave front Control (DM)



2 ~ 20 ps Fundamental

2 ~ 20 ps THG (263 nm)

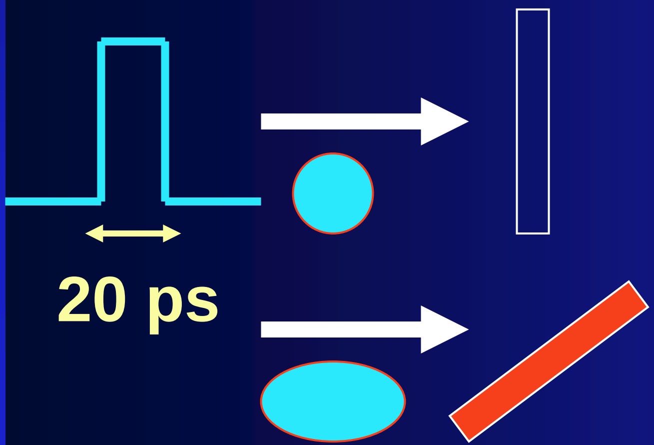
2. Motivation for beam quality control

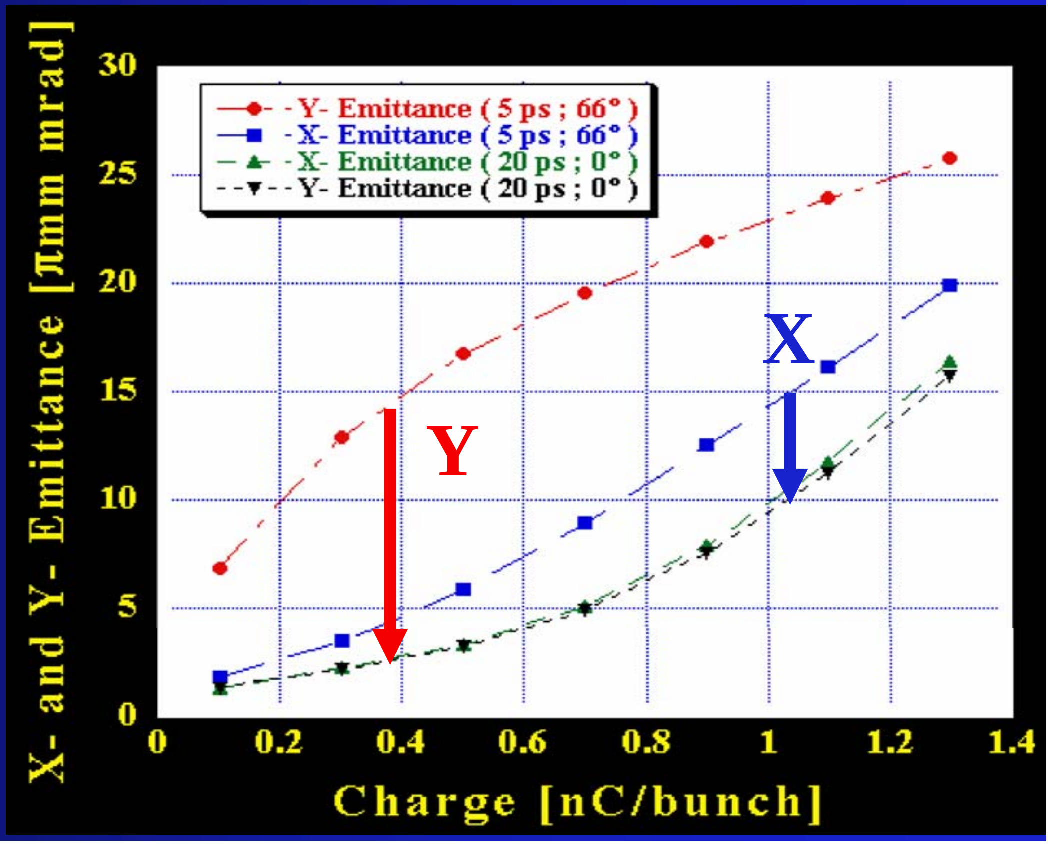
2-4. Influence of laser pulse shape and wave front

A) **Square Pulse with the optimal width ~ 20 ps**

B) **Wave front of laser pulse should reach at the same time to the cathode surface!**

Normal or Backward Incidence!

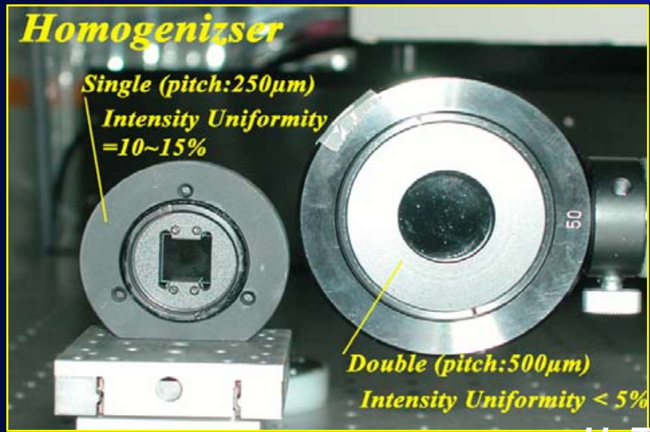


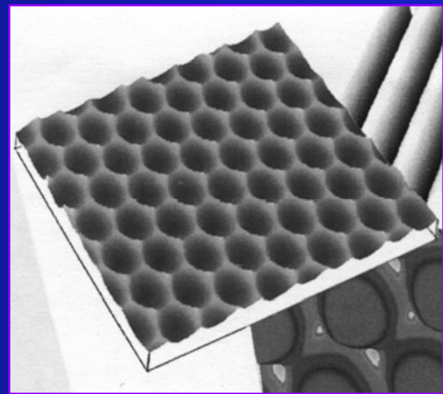


3. Optimization system of spatial profile

~ Microlens array (MLA) and Deformable Mirror (DM) ~

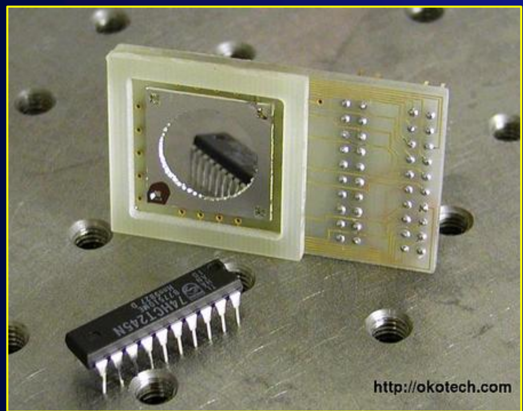
3-1. Spatial profile shaping with Microlens Array

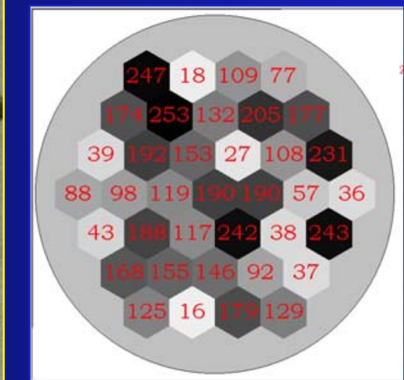




H. Tomizawa et al. EPAC'02, 1819, Paris, June 2002.

3-2. Spatial profile shaping with Deformable Mirror





\+ **Genetic Algorithms**

3-1. Spatial profile shaping with MLA

3-1-1. Microlens Array : effective & simple!!

combination with combination with Lens

Merit:

- relatively easy to adjust
- available in UV
- possible to homogenize asymmetrical beam

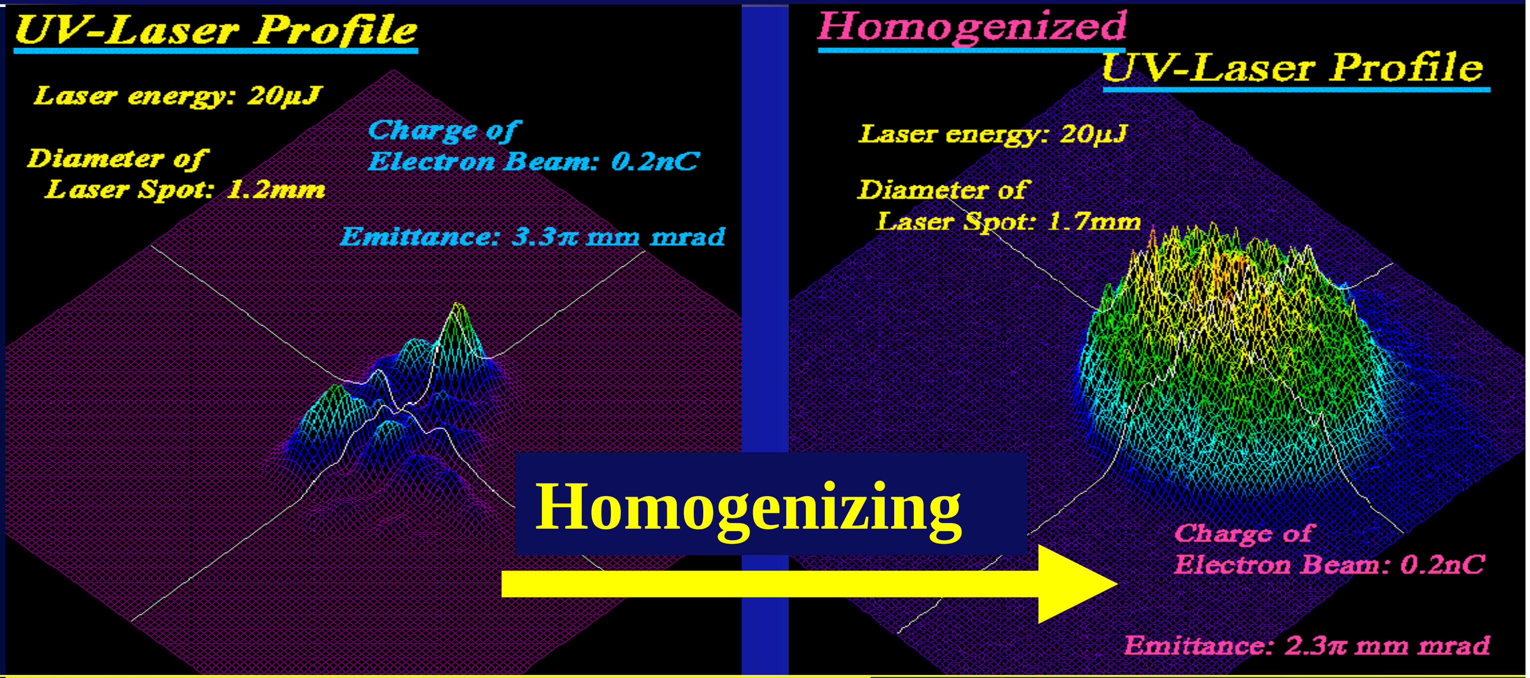
Demerit:

- impossible to get round image ~ hexagonal at most
- long working distance to get higher adjustability

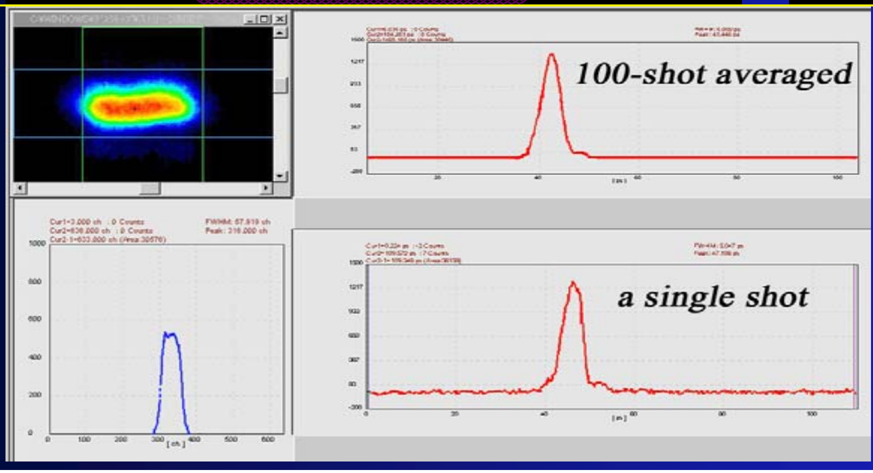
<u>Note that</u>: pitch >20 µm, pulse width >500 fs

3-1. Spatial profile shaping with MLA
3-1-2. Results of laser profiles with shaping

Spatial:



Temporal:



Spot size: 2.0 mm

Pulse width: 5 ps

(90-cm Fused Silica)

3-1. Spatial profile shaping with MLA

3-1-3. Results of emittance measurement

(3.1-MeV E-Beam; direct after Single-cell Gun; Double-Slit)

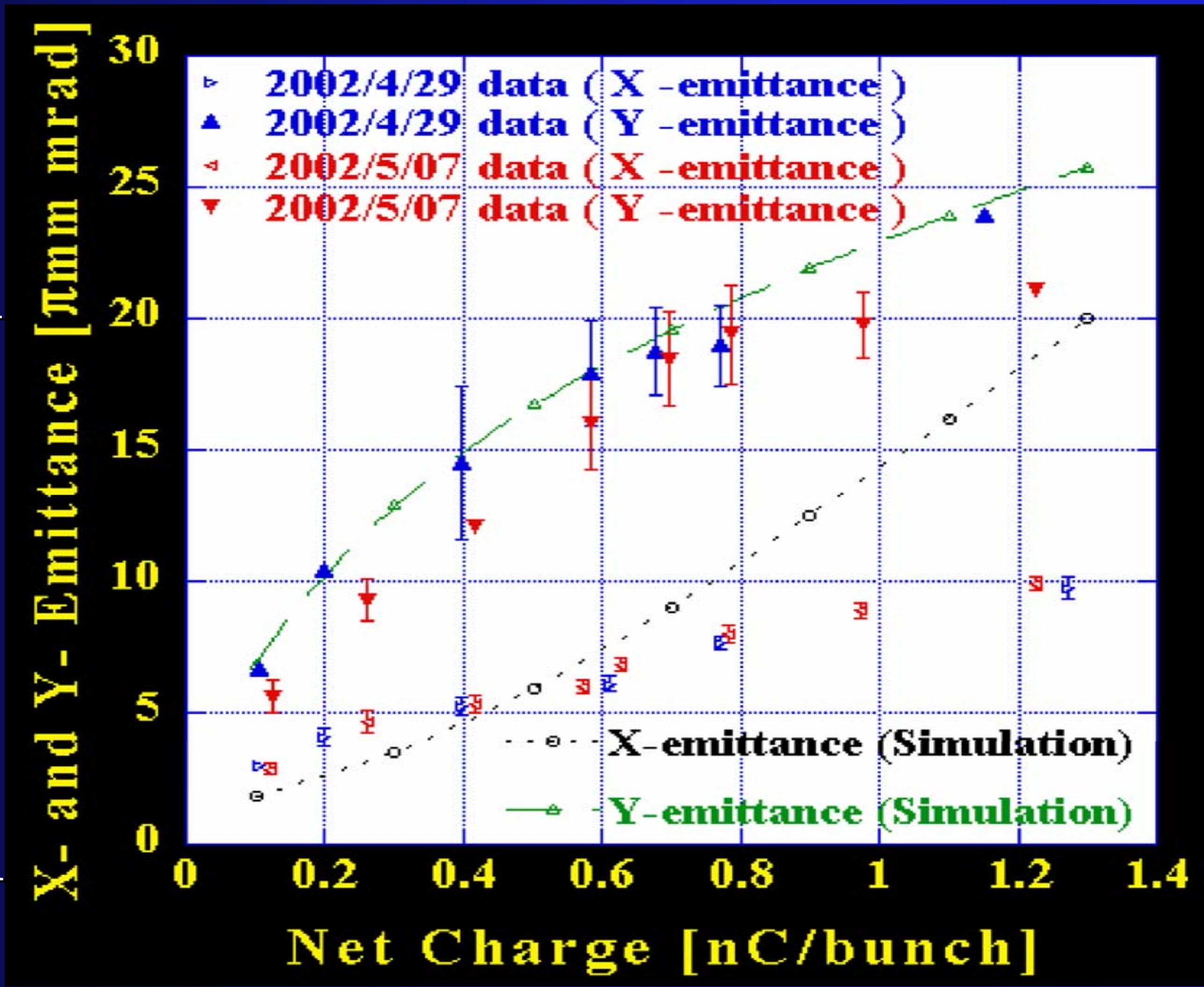
6.0 π mm mrad

May 2001

Homogenizing

2.0 π mm mrad

After Dec. 2001



H. Tomizawa et al. EPAC'02, 1819, Paris, June 2002.

3-2. Spatial profile shaping with DM

3-2-1. Deformable Mirror

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

Merit: *adjustable and actively controllable!!*

Demerit: *too many Possibility*: 256^{59}

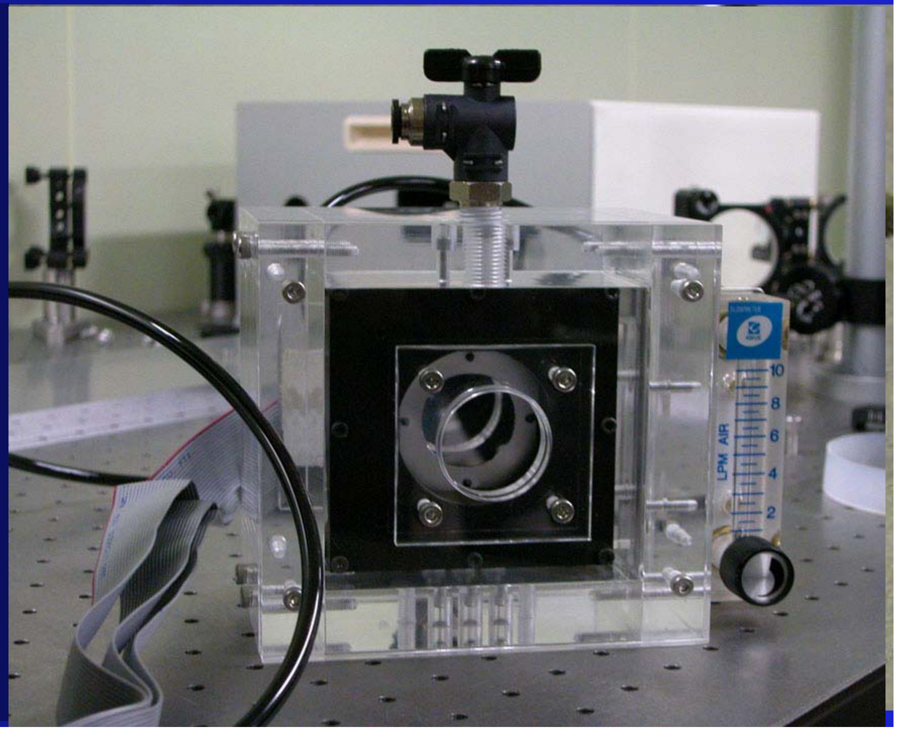
→ **Necessity of special algorithm to optimize**

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.

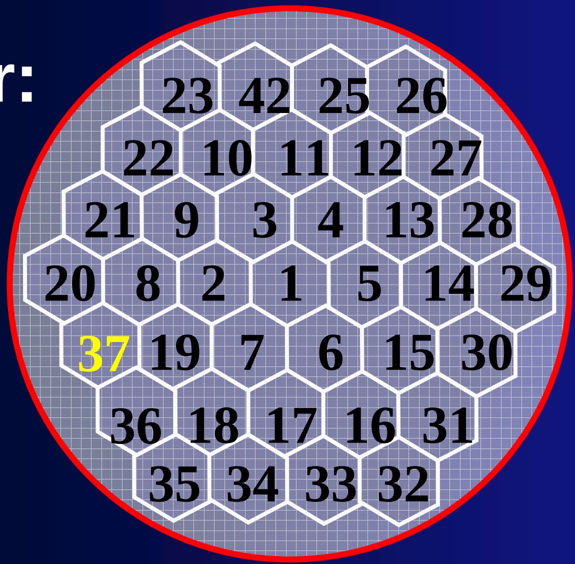


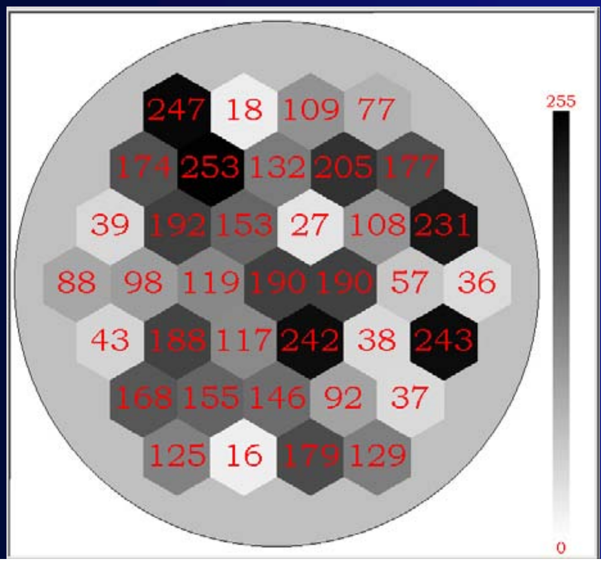
3-2. Spatial profile shaping with DM

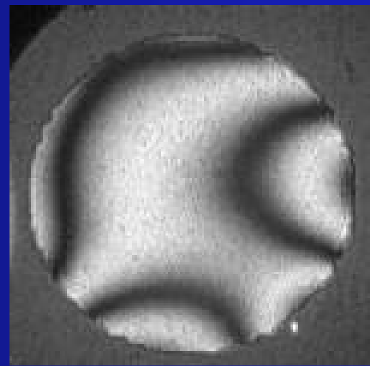
3-2-2. Deformable Mirror Actuator (ex. 37ch)

Voltage: <u>0 ~ 255 V</u>

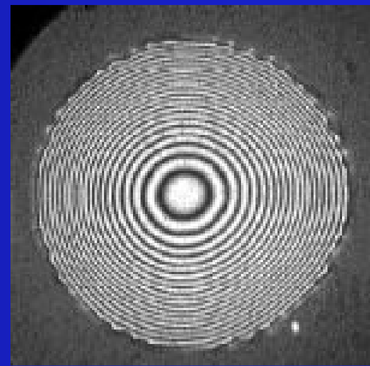
Actuator:



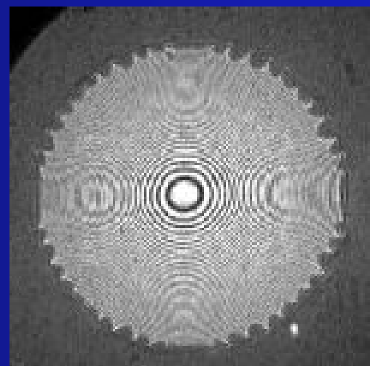




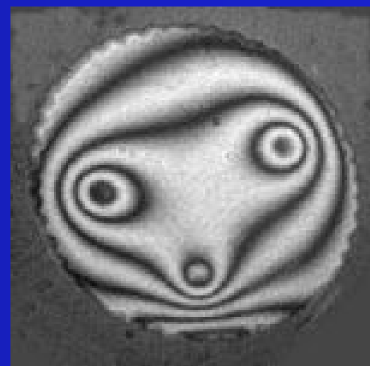
Initial State (All: 0V)



All: 125V



All: 255V (Max. Voltage)



Random Voltage

3-2. Spatial profile shaping with DM

3-2-3. Automation of optimization

Genetic Algorithm (GA) ~ Idea of Evolution ~

Genetic Algorithm

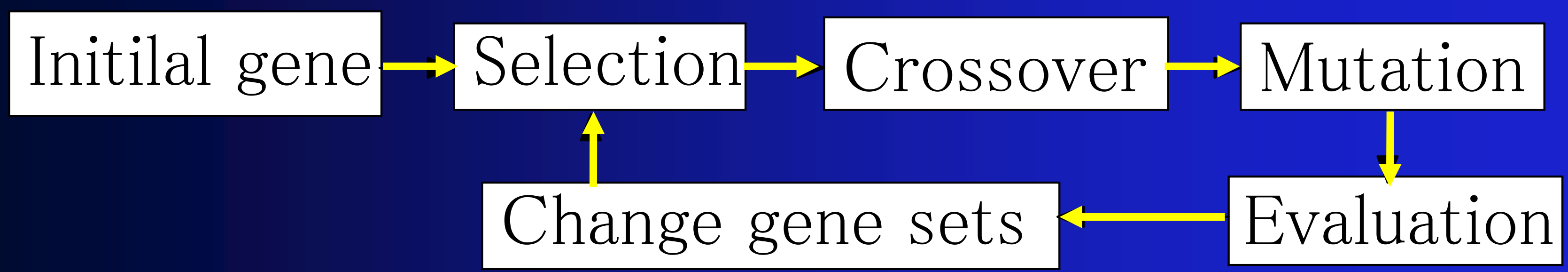
⟨Basic Process⟩

1) **Coding** : Digitize control parameters

gene | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |

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

3) Basic Process



3-2. Spatial profile shaping with DM

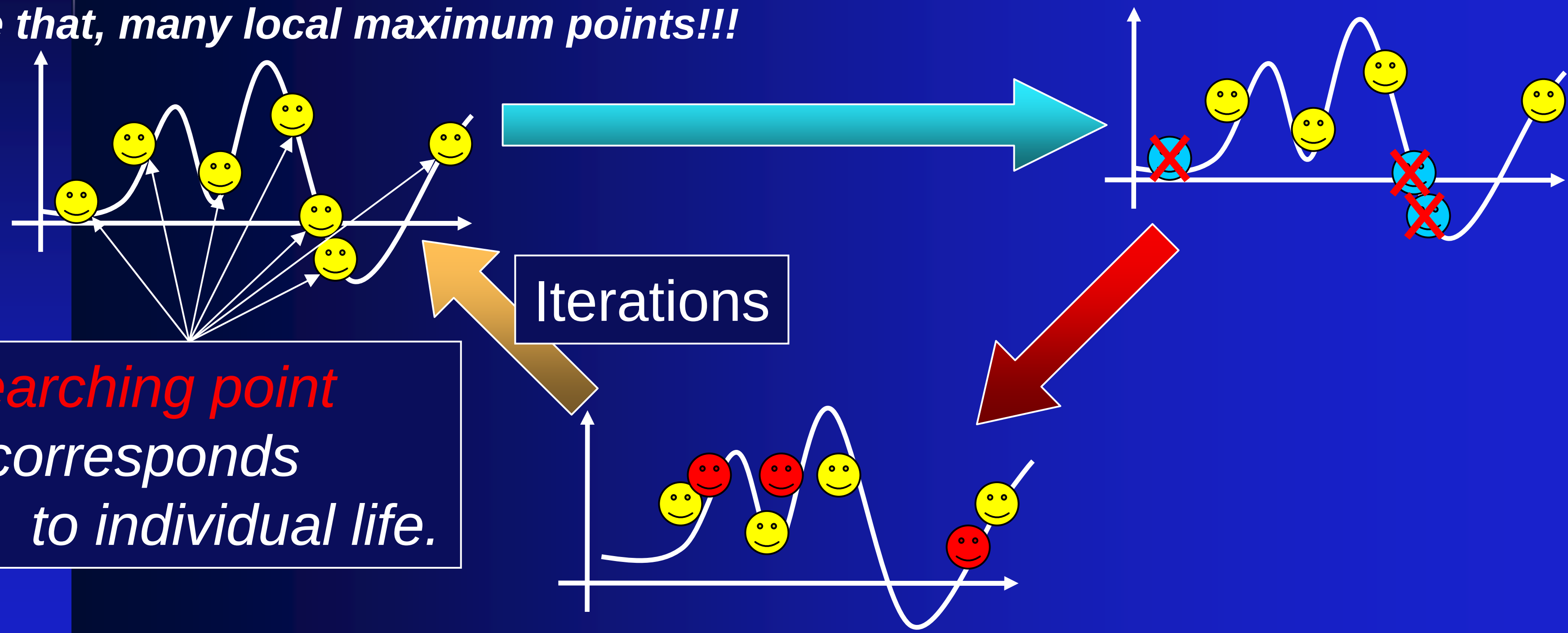
3-2-4. Example of Automation of optimization

～ Searching maximum point of *Fitting Function* ～

Example:
Search the Maximum Value!!

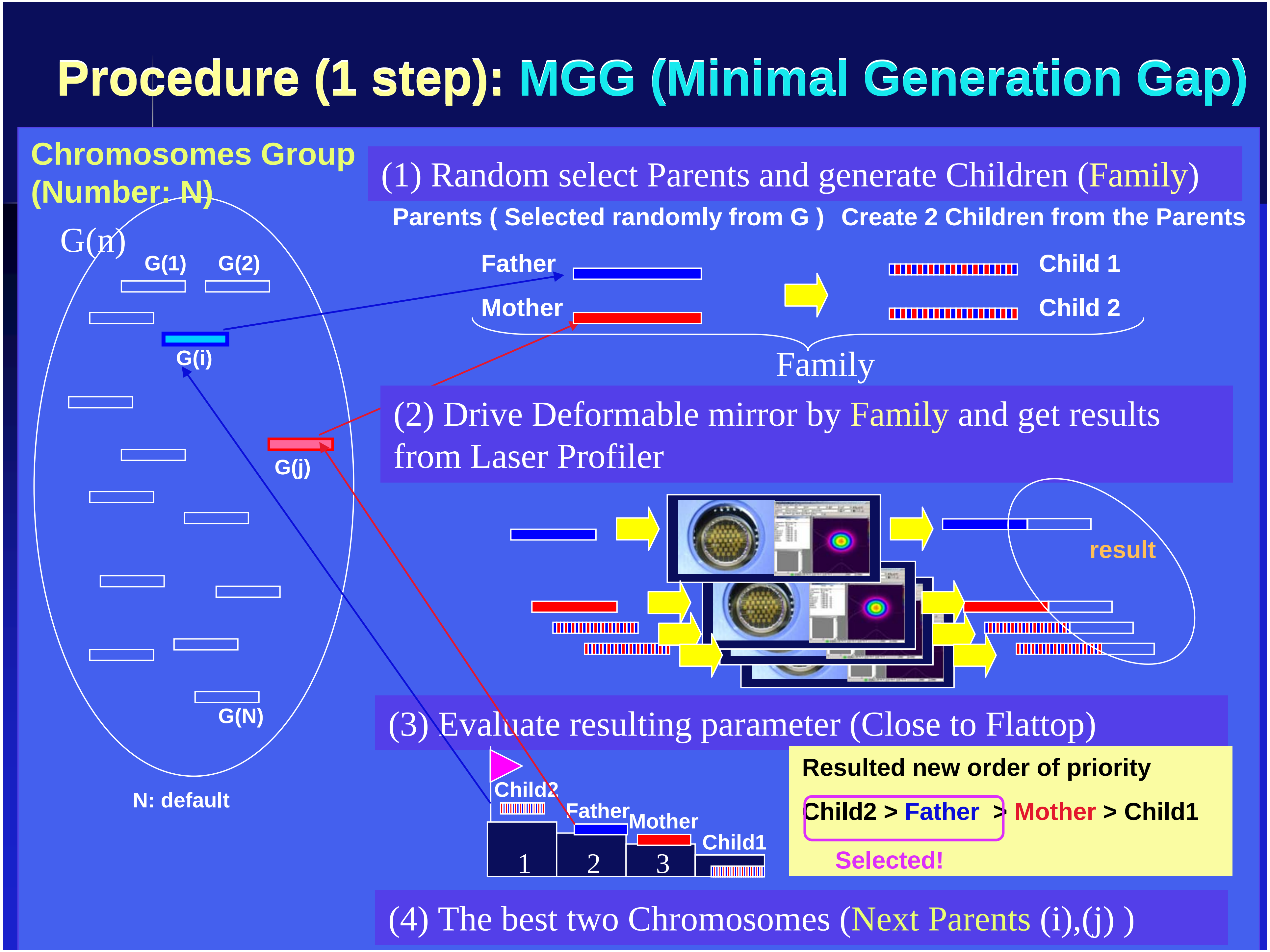
Searching points near by max. survive.

Note that, many local maximum points!!!



Searching point corresponds to individual life.

The survivors make new generation (Searching point).


Procedure (1 step): MGG (Minimal Generation Gap)
Chromosomes Group (Number: N)
G(n)
G(1)
G(2)
G(i)
G(j)
G(N)
N: default
(1) Random select Parents and generate Children (Family)
Parents (Selected randomly from G)
Create 2 Children from the Parents
Father
Mother
Child 1
Child 2
Family
(2) Drive Deformable mirror by Family and get results from Laser Profiler
result
(3) Evaluate resulting parameter (Close to Flattop)
Child2
Father
Mother
Child1
1
2
3
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

Random length

Child 1

Child 2

(2) 2 point Cross

Father

Mother

Random length

Child 1

Child 2

(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

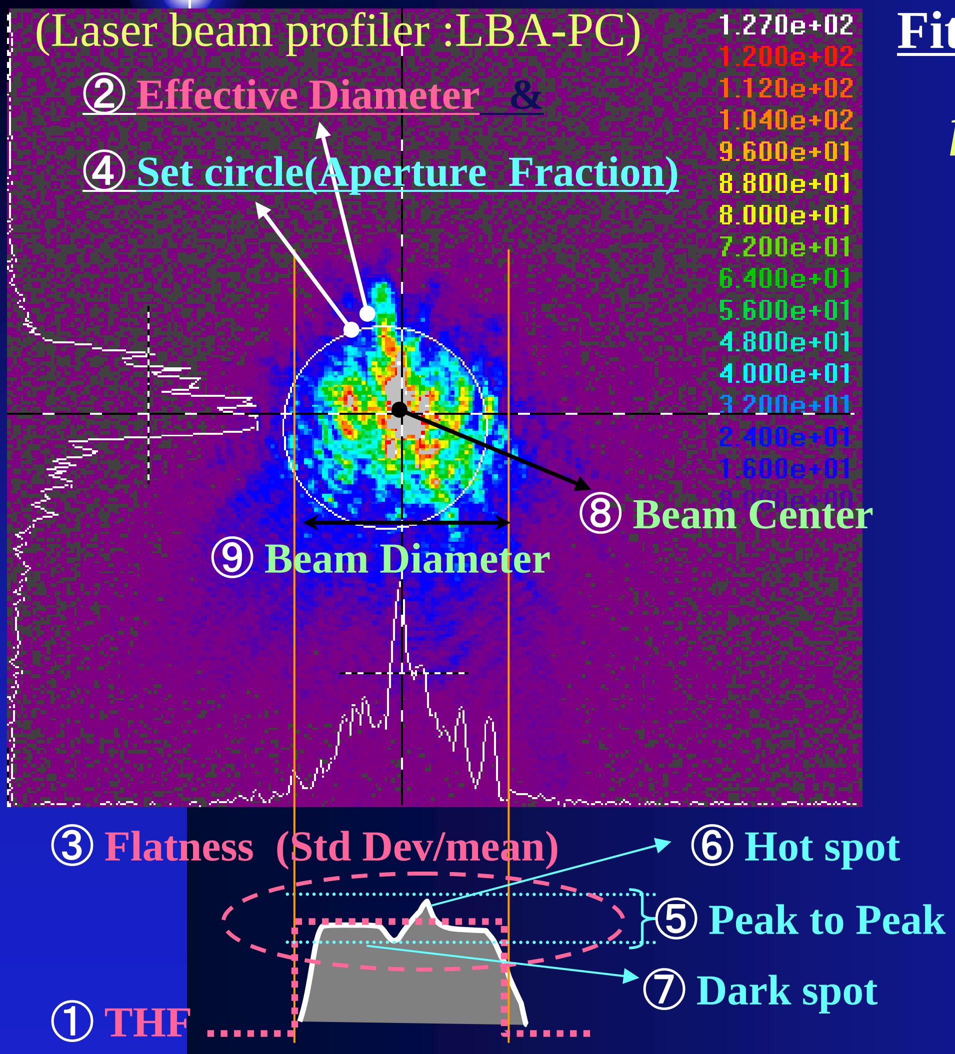
Child 2

(Child 2 = $\overline{\text{Child1}}$)

The reason to chose：simple to program

Fitting Function to evaluate Flattop profiles

Laser profile during optimization



Intensity distribution (cross section)

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

f(profiles) = *a*① + b② + c③ +d④ + e⑤ + f⑥ + g⑦ + h⑧ + i⑨

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

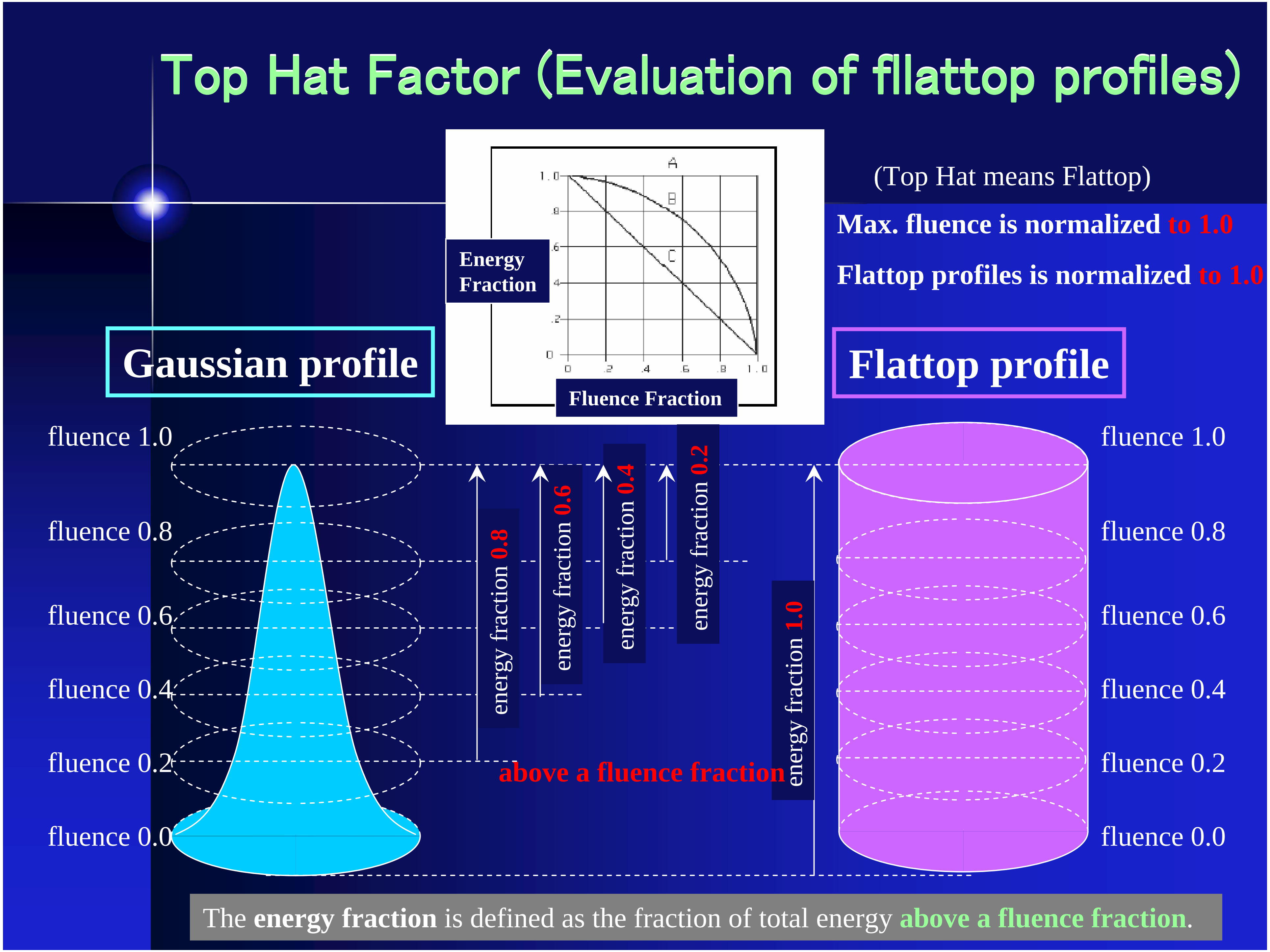
5.Peak-to-peak: Minimize the difference between the max. and min. in a flattop area

6.Hot Spot(max.): Minimize the max. in a flattop area

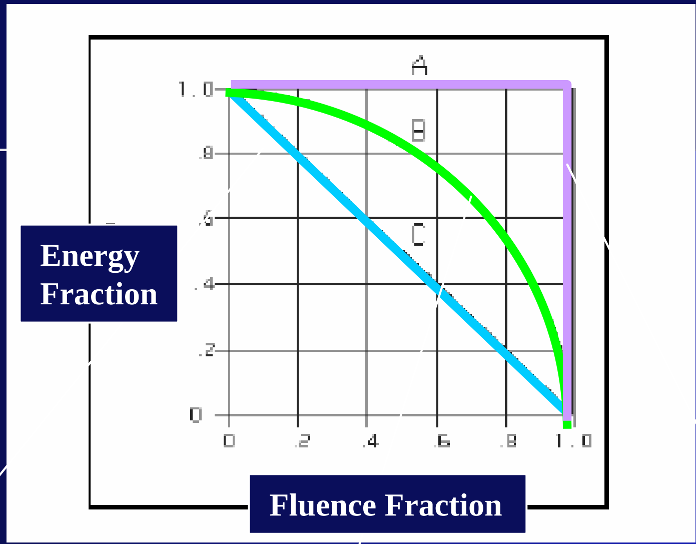
7.Dark Spot(min.): Maximize the min. in a flattop area

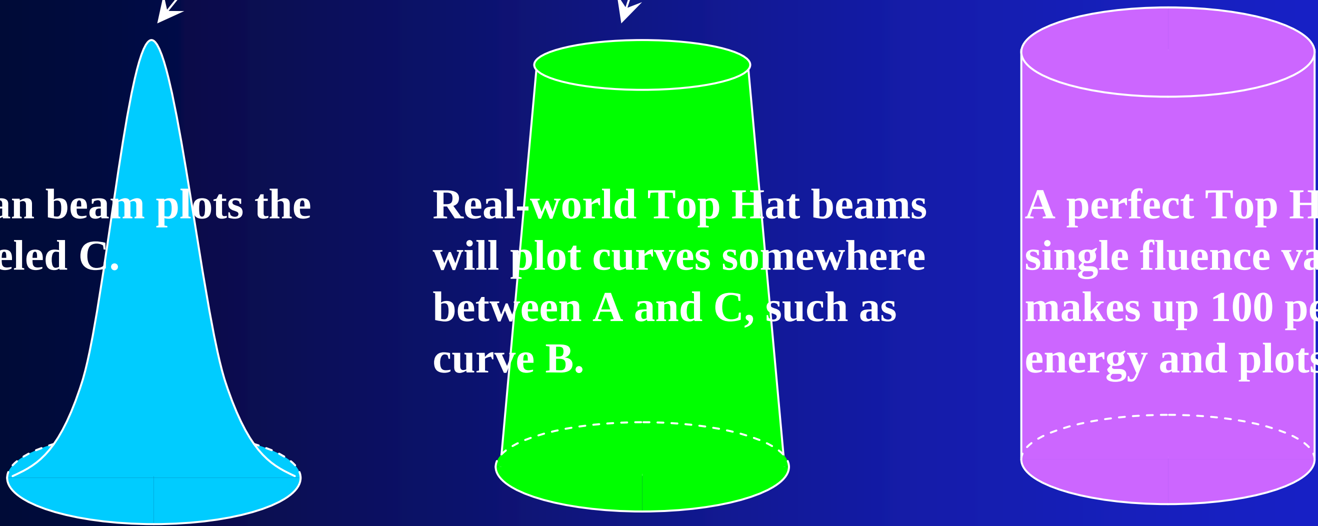
8.Beam Center: Minimize the difference from the initial center position (x, y)

9.Beam Diameter: Minimize the difference from the set diameter



Top Hat Factor (Evaluation of fllattop profiles)
(Top Hat means Flattop)
Max. fluence is normalized to 1.0
Flattop profiles is normalized to 1.0
Energy Fraction
Fluence Fraction
A
B
C
Gaussian profile
Flattop profile
fluence 1.0
fluence 0.8
fluence 0.6
fluence 0.4
fluence 0.2
fluence 0.0
energy fraction 0.8
energy fraction 0.6
energy fraction 0.4
energy fraction 0.2
energy fraction 1.0
above a fluence fraction
The energy fraction is defined as the fraction of total energy above a fluence fraction.





A Gaussian beam plots the curve labeled C.

Real-world Top Hat beams will plot curves somewhere between A and C, such as curve B.

A perfect Top Hat has a single fluence value that makes up 100 percent of energy and plots curve A.

Gaussian profile

Real-world Flattop beams

Perfect Flattop beams

Weight of each term of fitting function for *Flattop*

~ decided by comparing convergence status ~

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

User weight(P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8, P_9)

$$f(\,profiles\,) = a \cdot P_1 \cdot R_{thf} + b \cdot P_2 \cdot R_{ed} + c \cdot P_3 \cdot R_f + d \cdot P_4 \cdot R_{ap} + e \cdot P_5 \cdot R_{pp} + f \cdot P_6 \cdot R_{hs} + g \cdot P_7 \cdot R_{ds} + h \cdot P_8 \cdot R_{bc} + i \cdot P_9 \cdot R_{bd}$$

R_{thf} : Result of THF

R_{ed} : Result of Effective diameter

R_f : Result of Flattness

R_{ap} : Result of Aperture Fraction

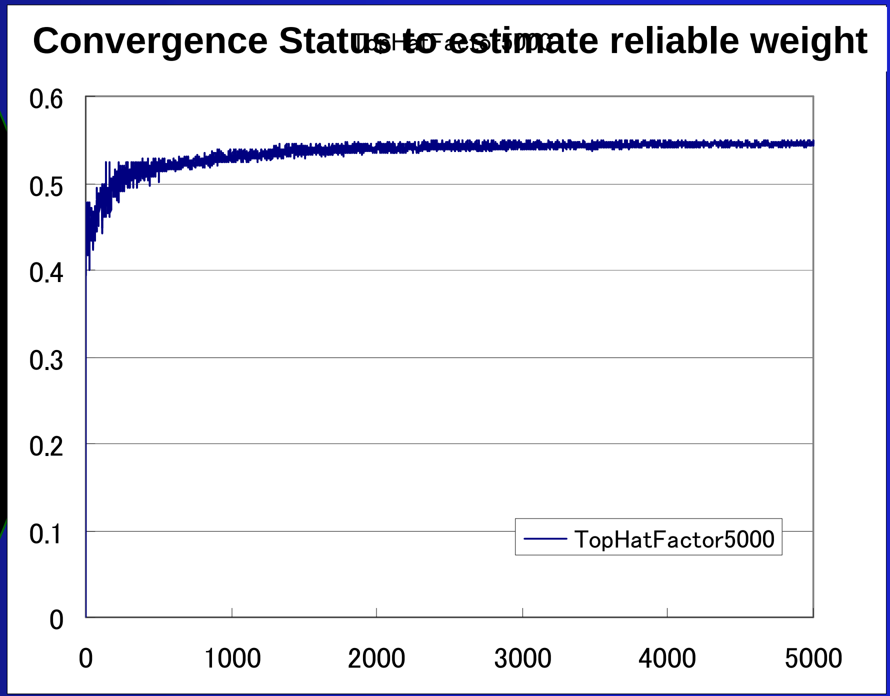
R_{pp} : Result of Peak to Peak

R_{hs} : Result of Hot spot

R_{ds} : Result of Dark spot

R_{bc} : Result of Beam center

R_{bd} : Result of Beam diameter

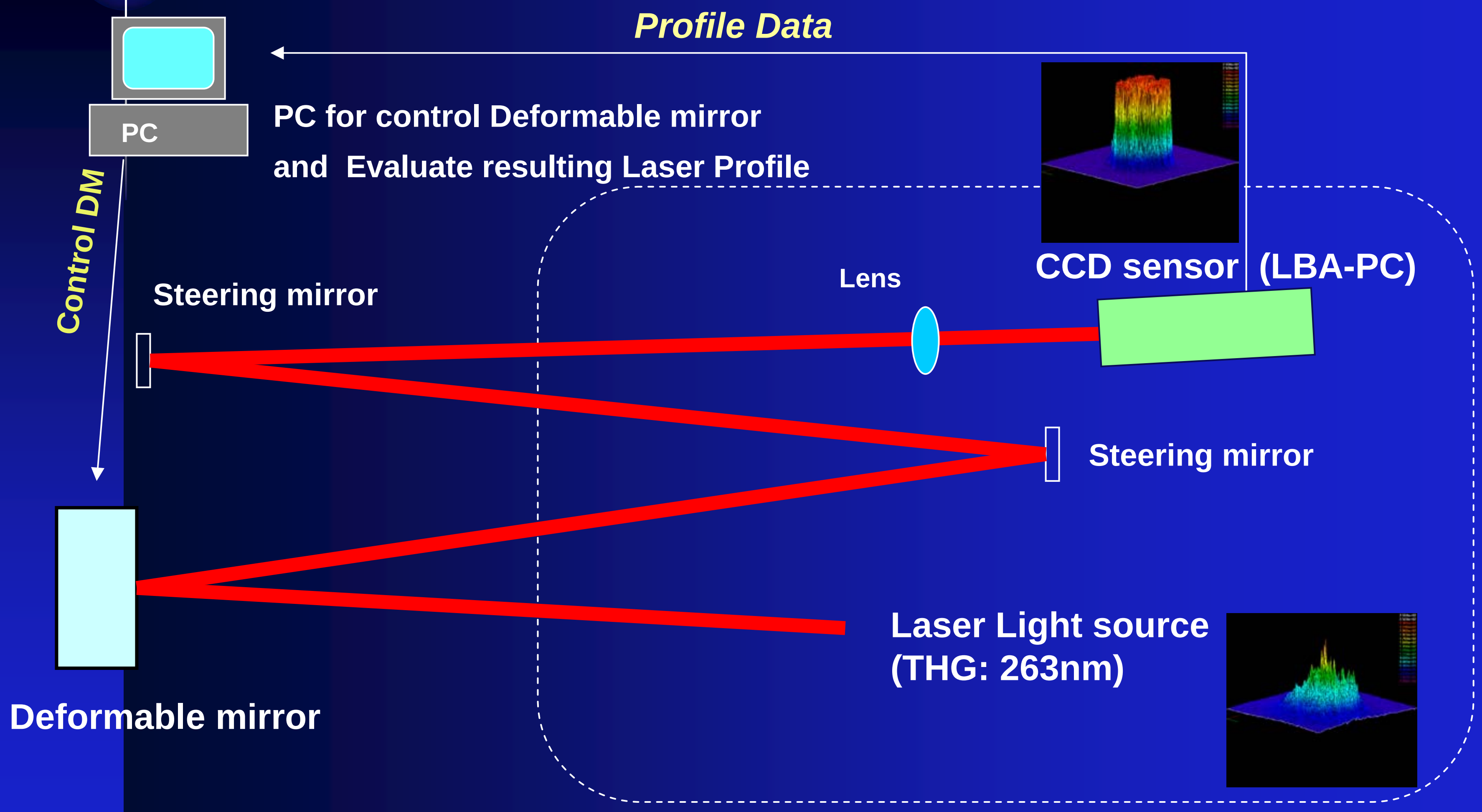


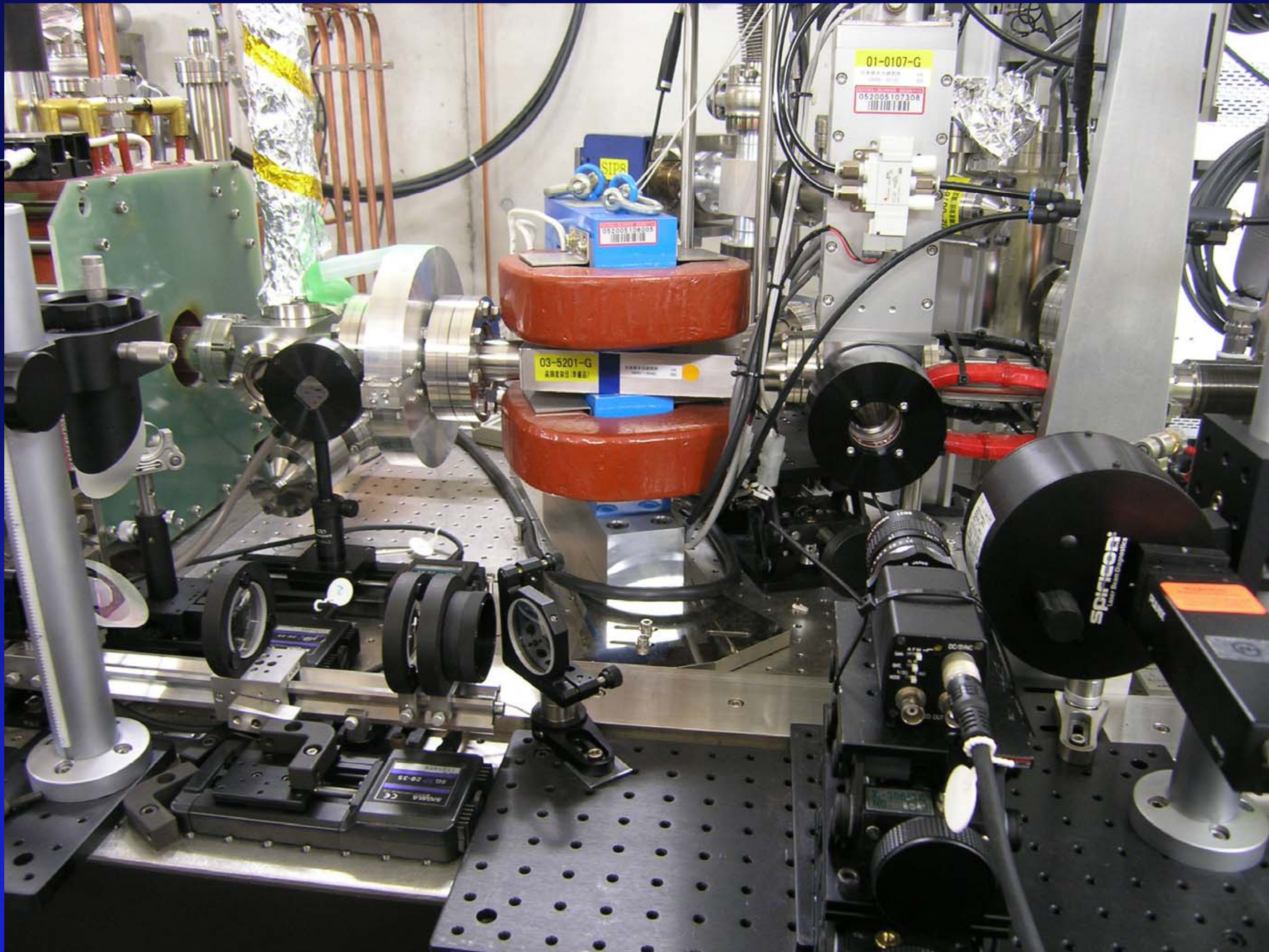
Weight of each term of fitting function for *Flattop*

~ 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

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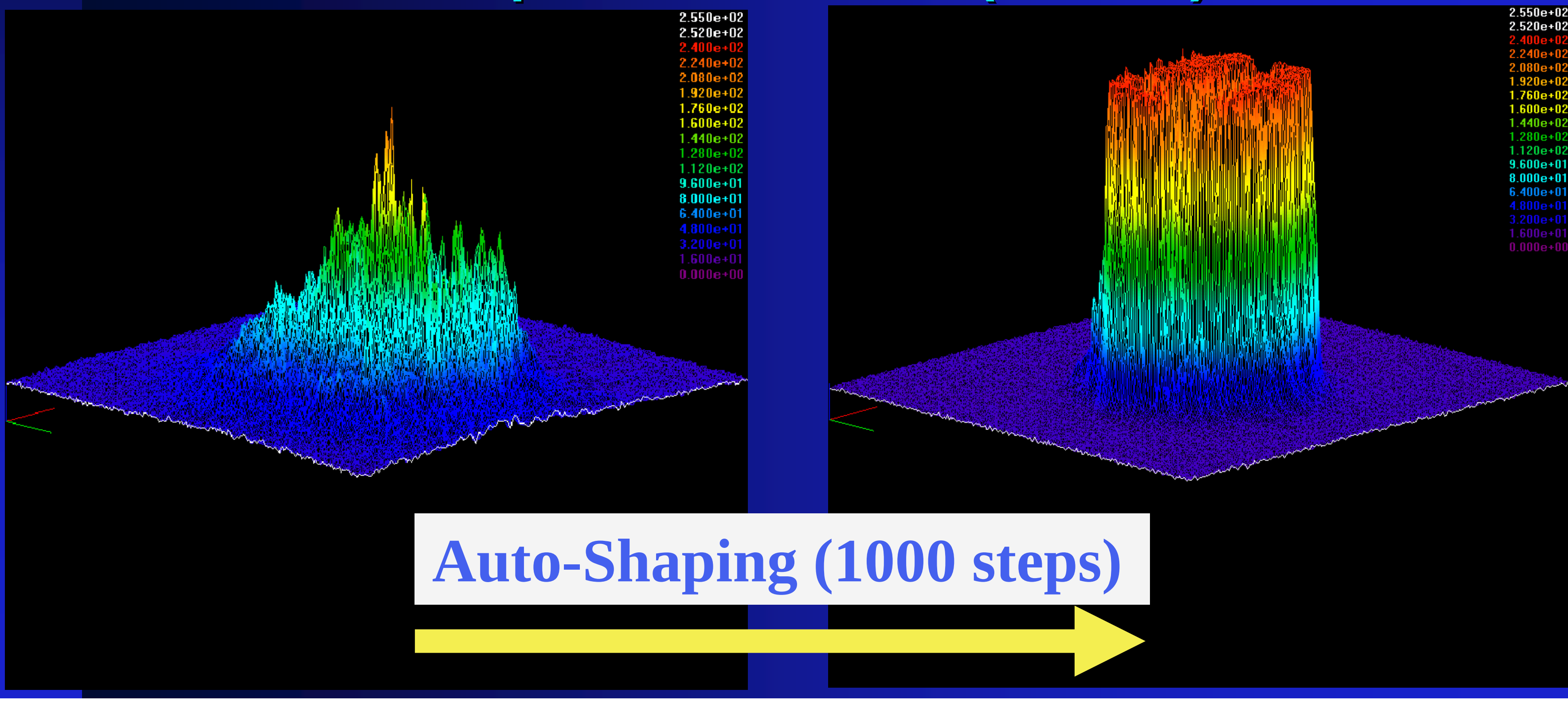
052005107308
03-5201-G
spiricon

3-2. Spatial profile shaping with DM

3-2-4. 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)**



3-3. Spatial profile shaping with AL

Aspheric Lens: not adjustable (M^2 ~ 1.0)

~ If laser spatial profile is perfect Gaussian ~

Merit:

- perfect Flattop
- keep shape in 100mm

Demerit: ***No Adjustability!!***

- need perfect Gaussian
- need exact $1/e^2$ diameter
- impossible optical polishing
  ~ Difficulty for UV
- less choice of material
  ~ ZnSe or CaF_2

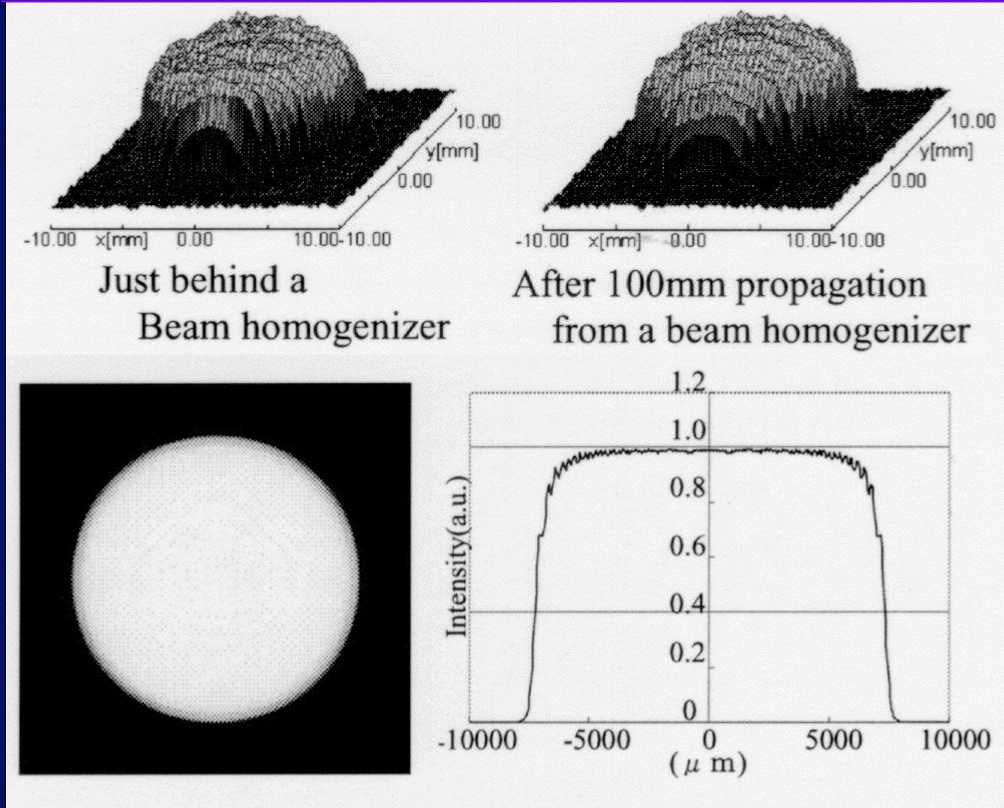
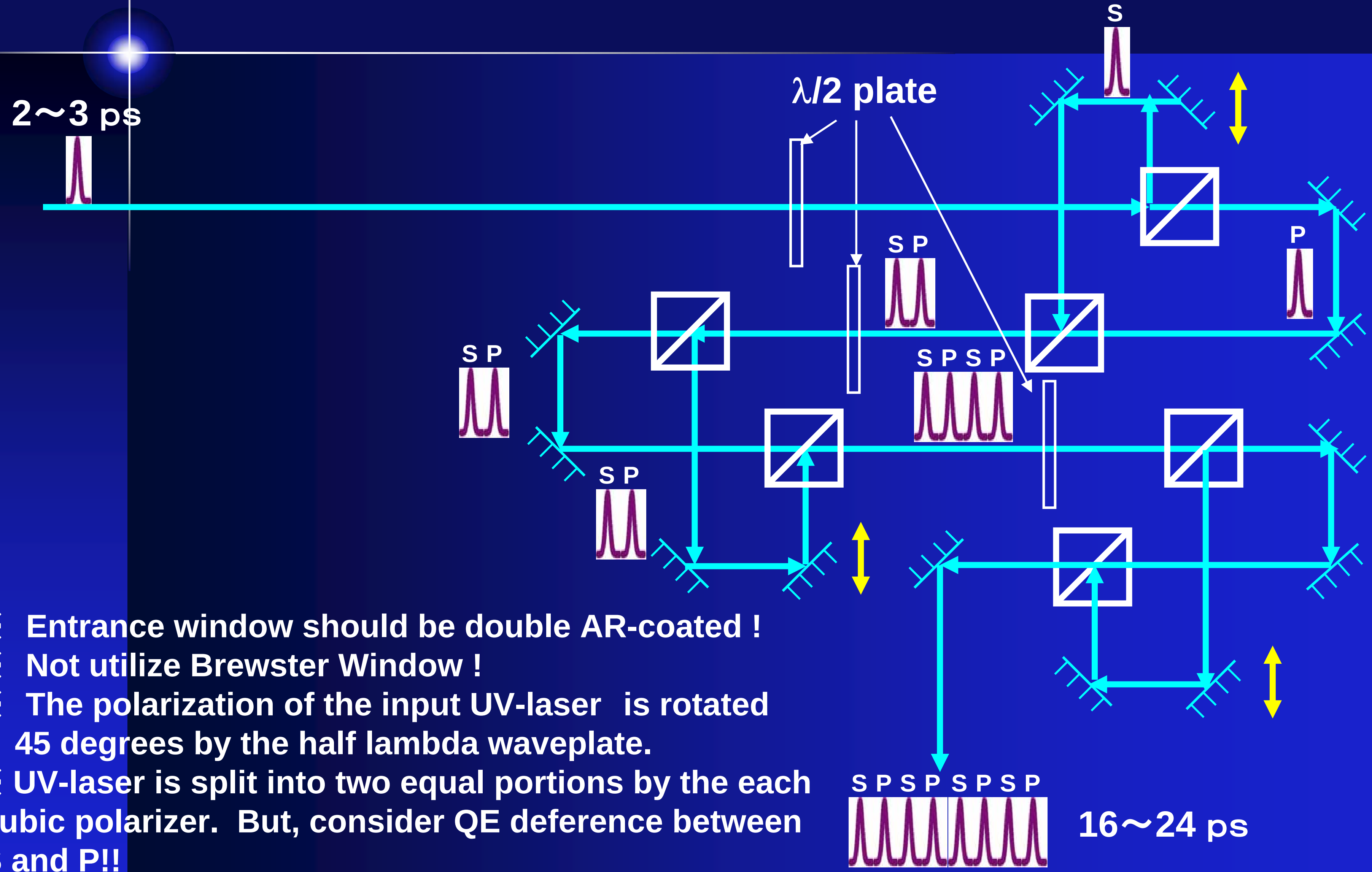


Fig.12 Calculated intensity of the beam homogenized by the designed aspheric homogenizer

T. Hirai et al. SPIE, Conf. 4443, 29 July to August 2001.

4. Optimization system of temporal profile

4-1-1. UV-Pulse Stacker



※ Entrance window should be double AR-coated !

※ Not utilize Brewster Window !

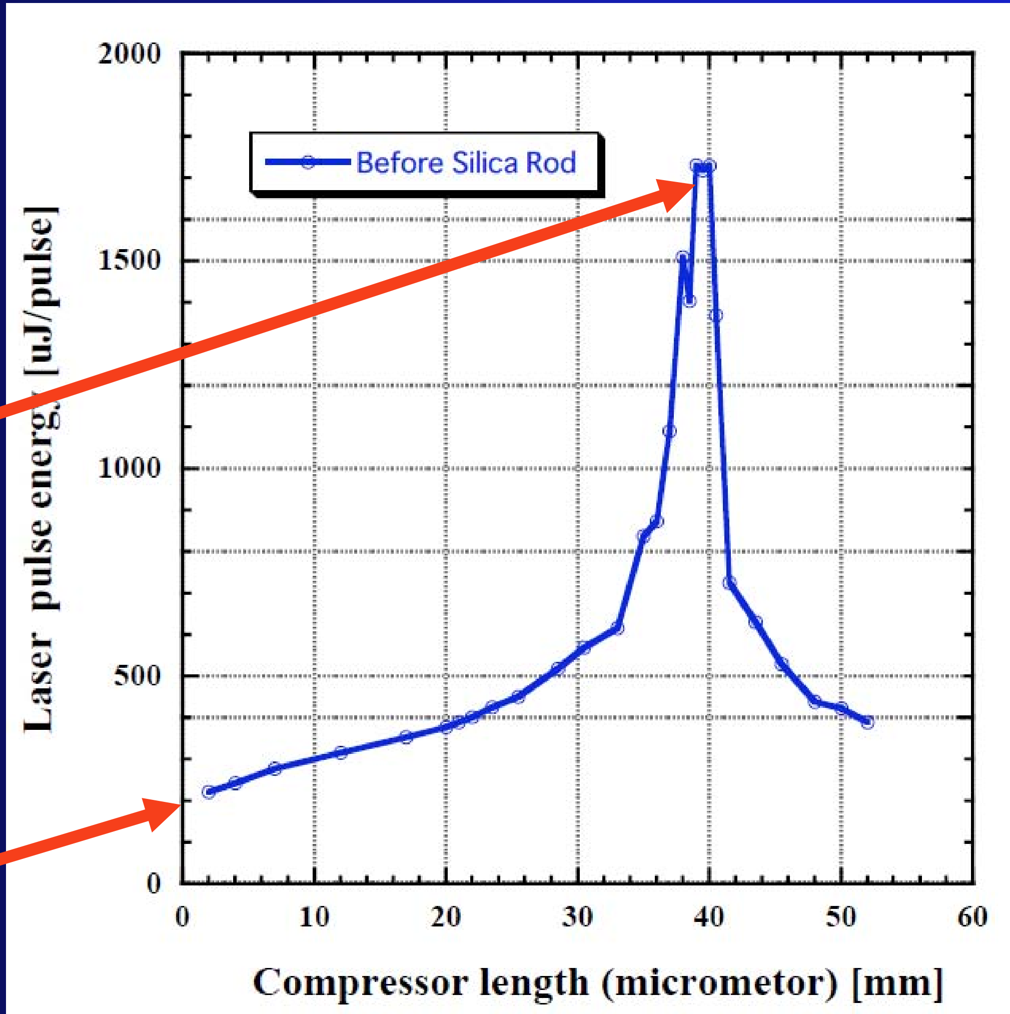
※ The polarization of the input UV-laser is rotated 45 degrees by the half lambda waveplate.

※ UV-laser is split into two equal portions by the each cubic polarizer. But, consider QE deference between S and P!!

4. Optimization system of temporal profile

4-1-2. Chirped pulse with deferent compressor length

~ Optimal THG crystal thickness to keep its broad bandwidth ~



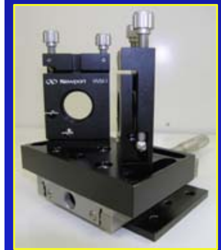
100 fs

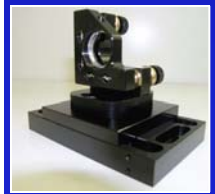
2~3 ps

Positive ⇦ ⇨ Negative

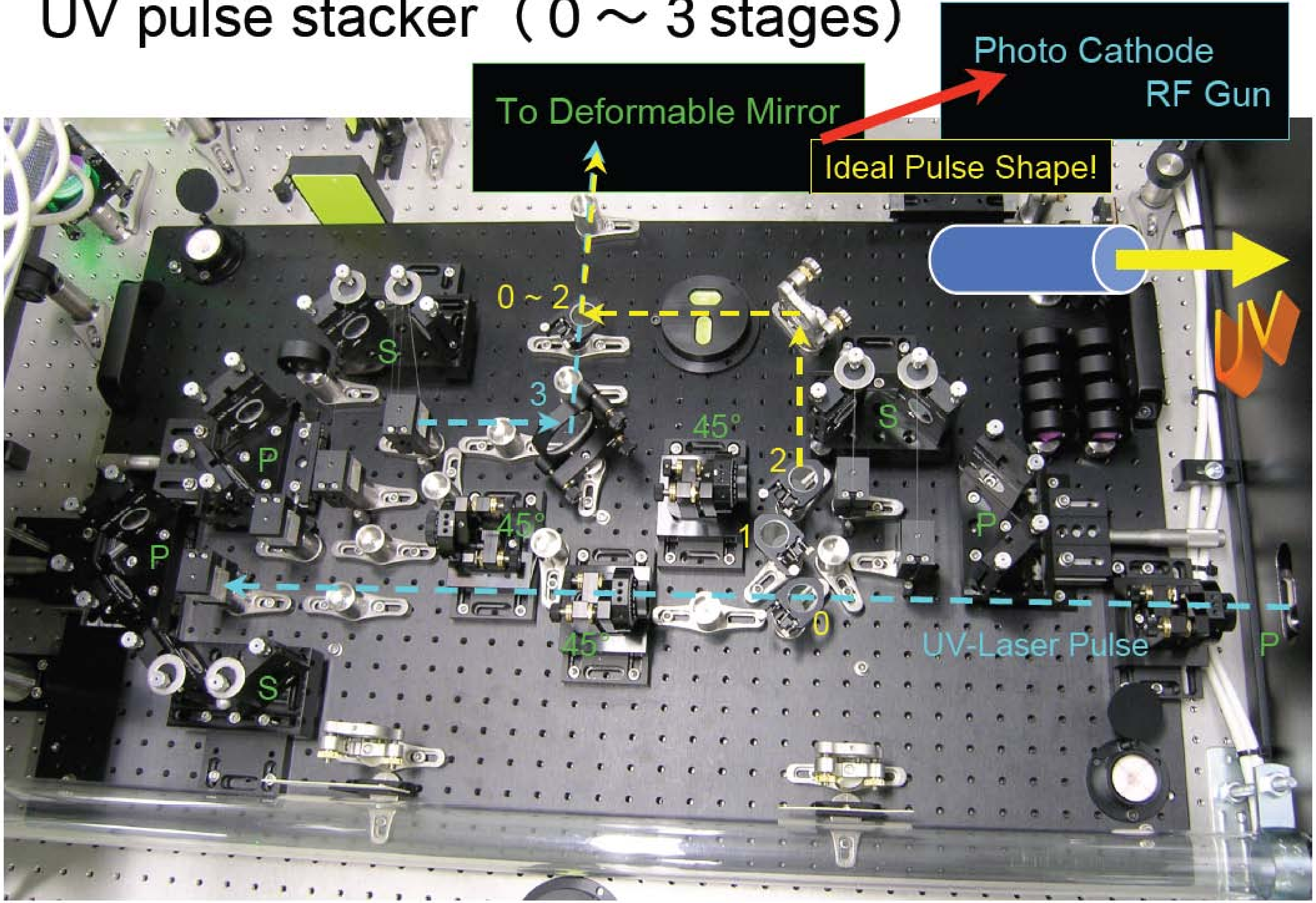
4. Optimization system of temporal profile

4-1-3. Developed UV-Pulse Stacker

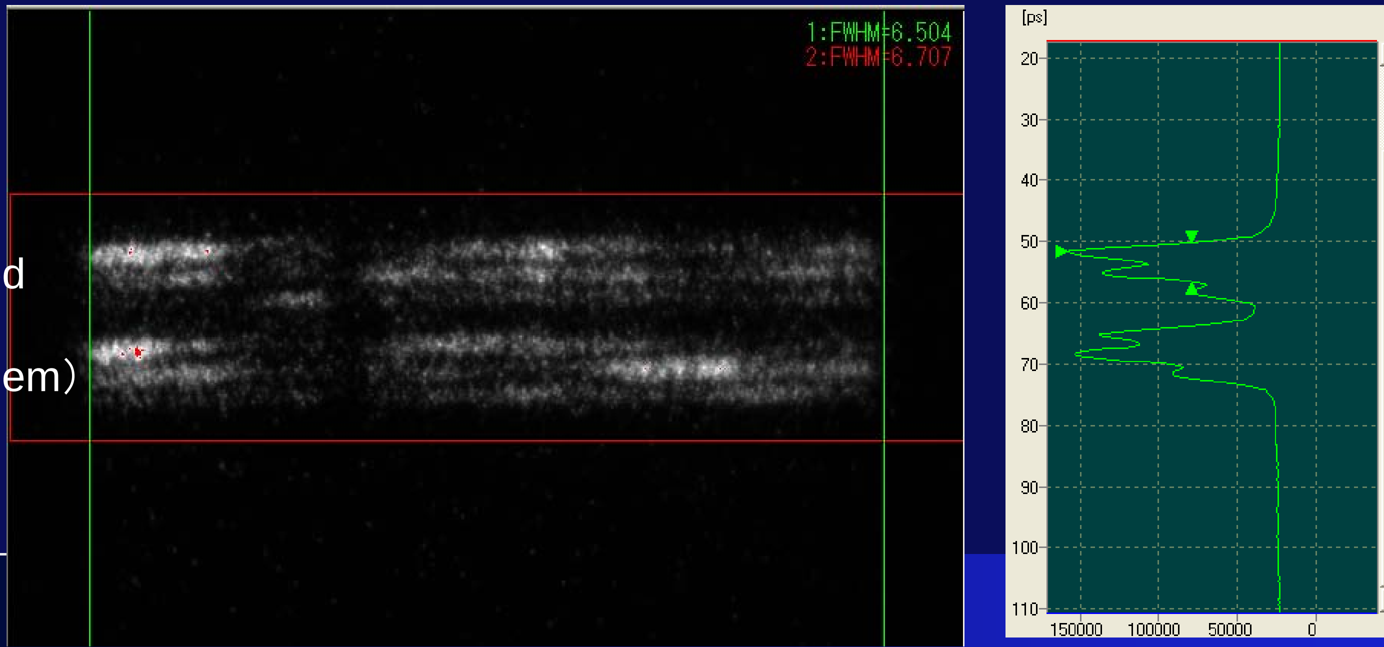




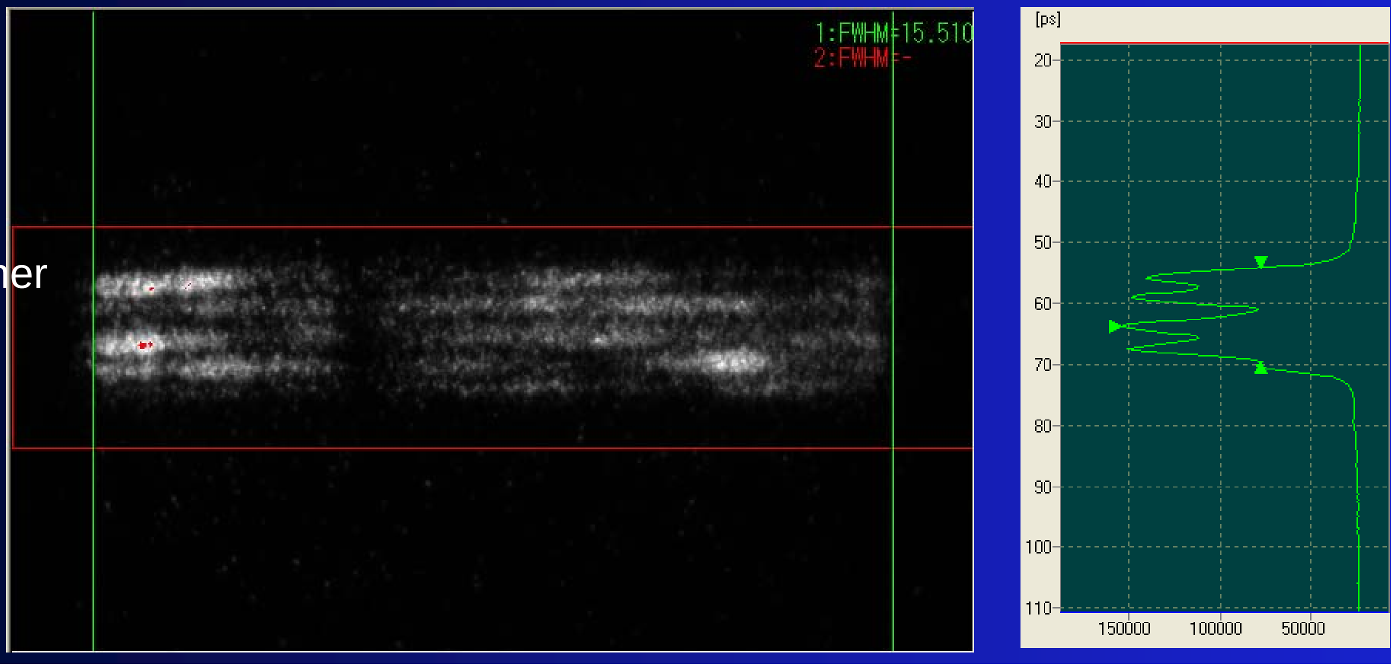
UV pulse stacker（0～3 stages）



Two 6.5-ps stacked Pulses
（14 ps between them）

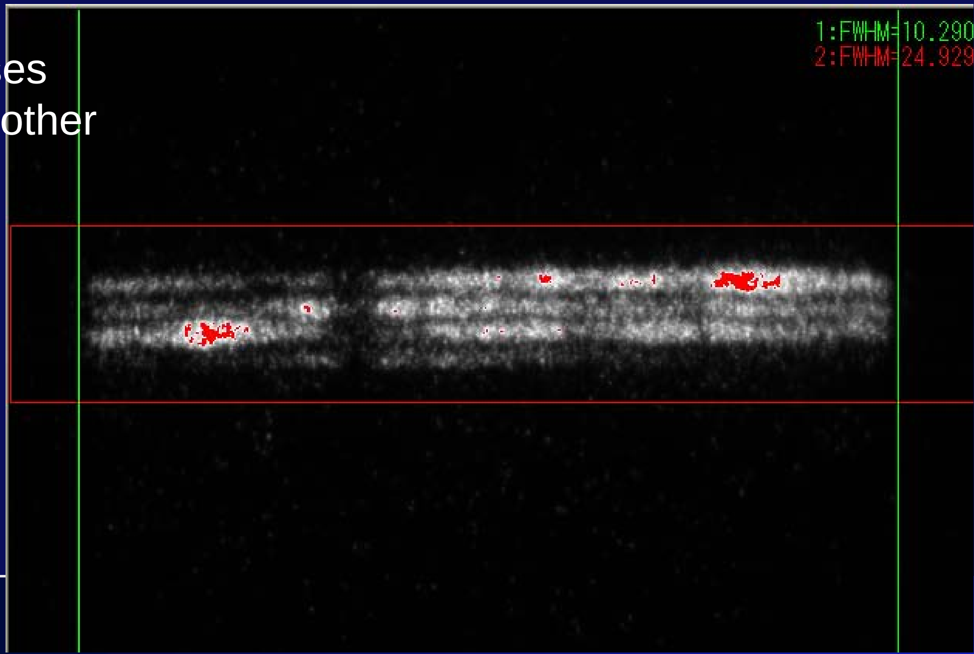


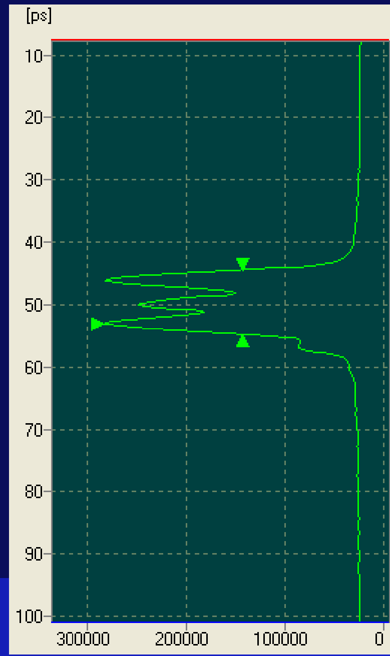
Shifting
optical delay 3



All stacked together
（15.5 ps FWHM）

Two stacked pulses overlapped each other (10 ps FWHM)



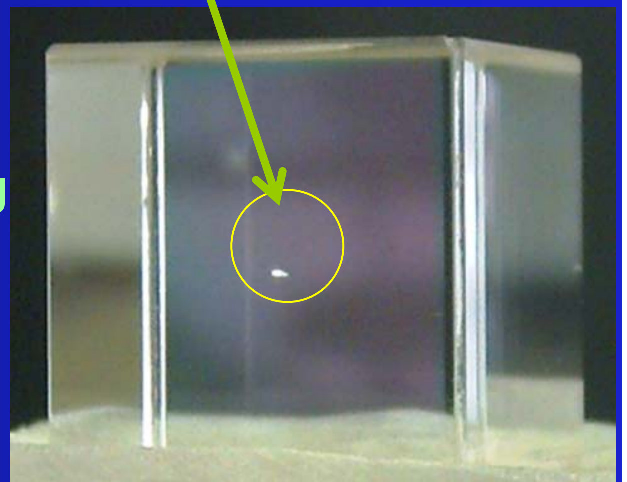


※ **3-stage UV- Pulse Stacker was successful !**

※ **Polarizing Beamsplitter cube (Optical Cement) was damaged with high intensity of UV-Laser ! Preparing Optical Contact (150 times stronger!) .**

Also, because of nonlinear effect, efficiency is lower. The efficiency at the first stages is lower than following stages!

Optical Cement was damaged!



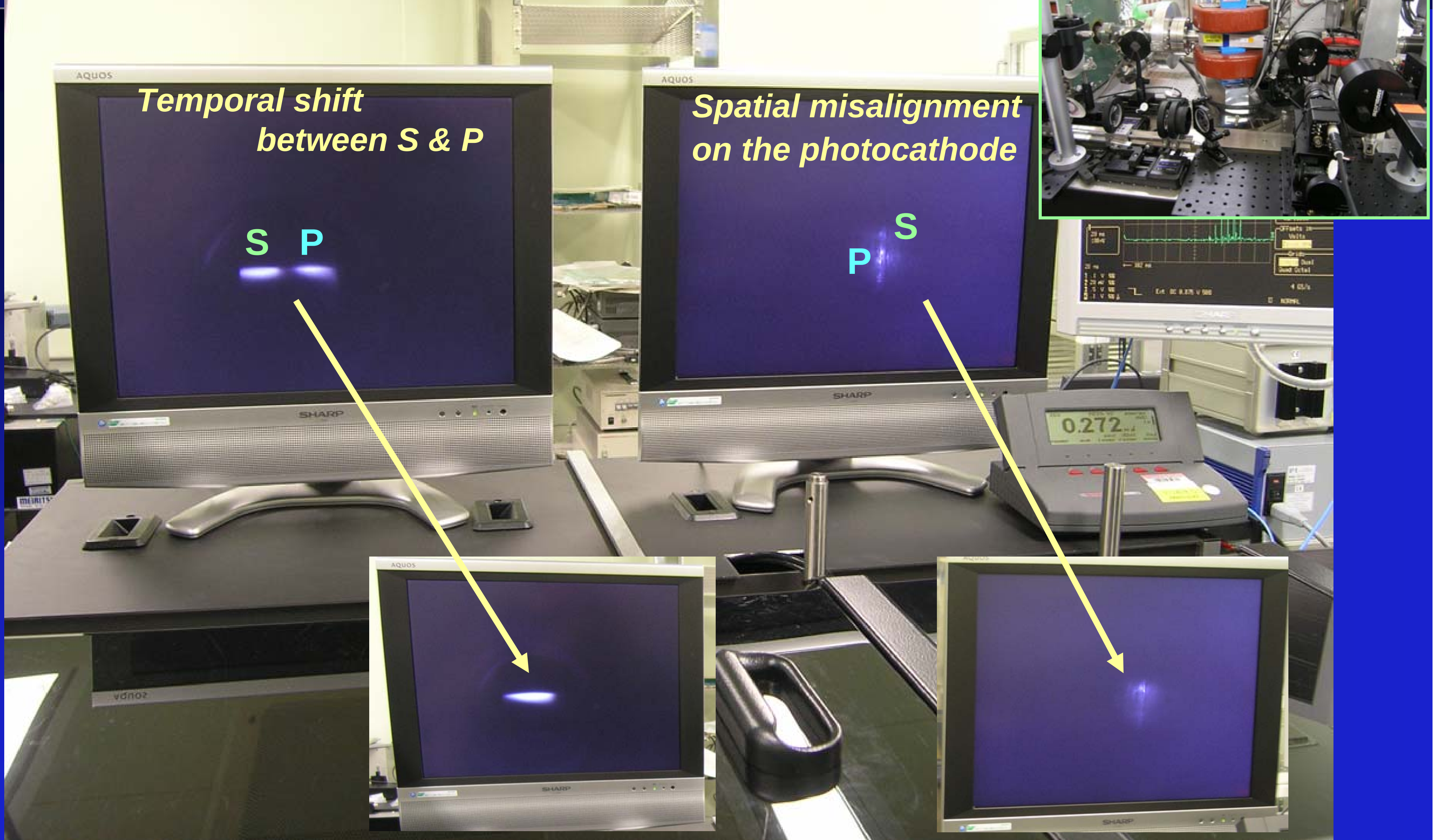
Ex.) Initial Pulse：2.9 ps；731 μ J/pulse

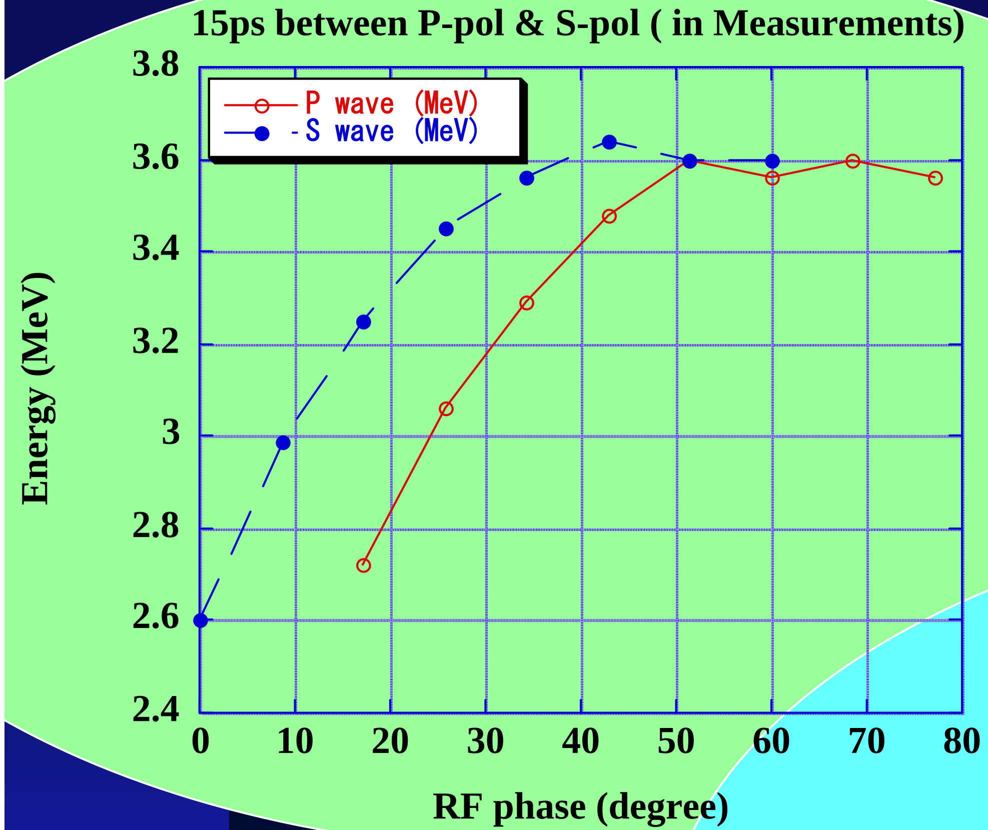
Efficiency @ 1st： 65%（ 474 μ J/pulse ）

Efficiency @ 2nd ： 79%（ 373 μ J/pulse ）

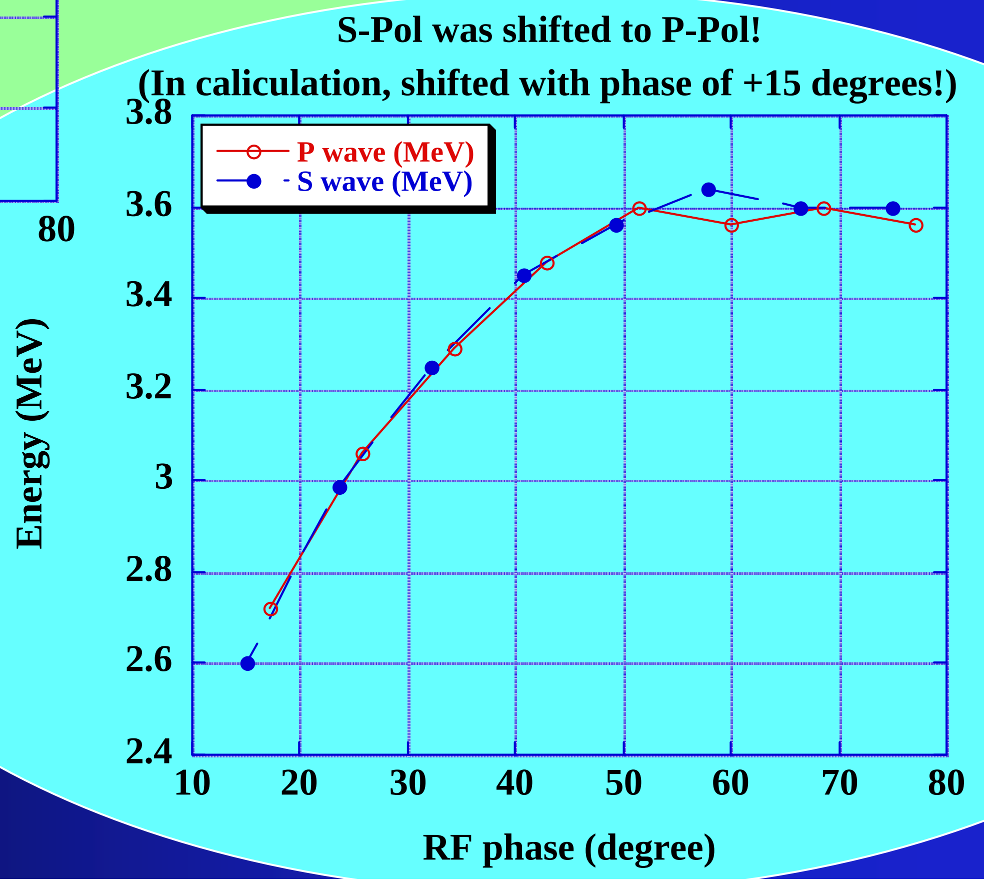
Efficiency @ 3rd ： 84%（ 314 μ J/pulse ）

Usage Photocathode with energy analyzer as a streak camera



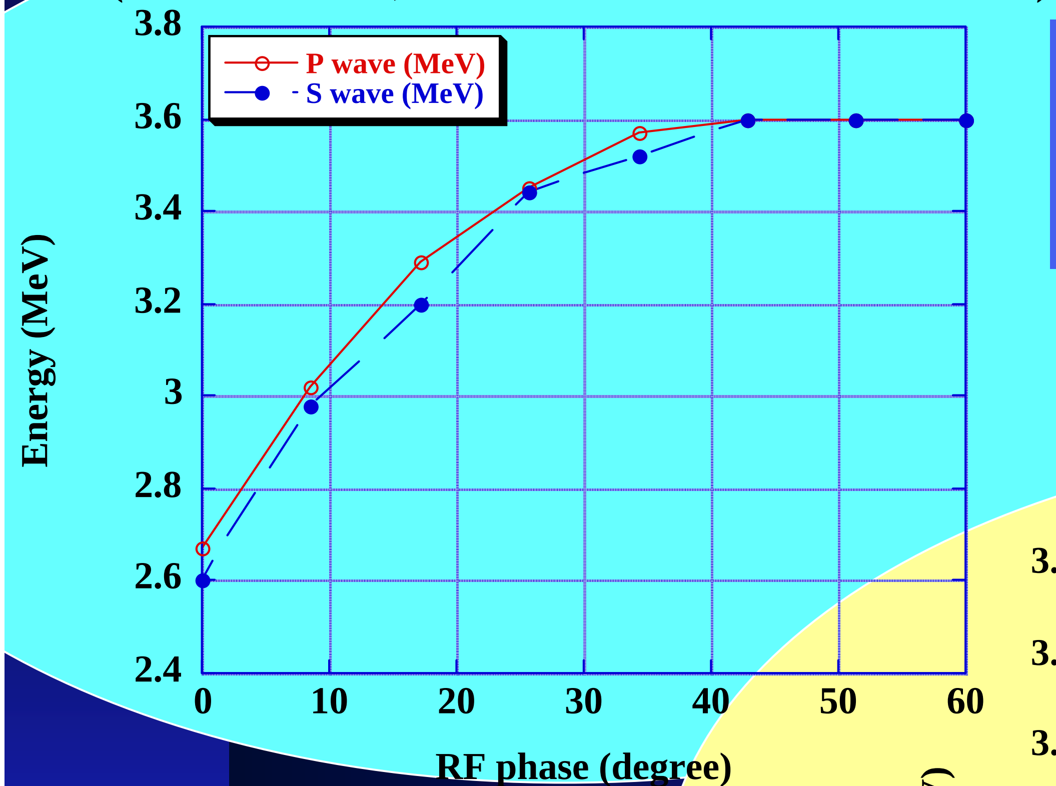


Measured time deference between two beamlets: 15ps



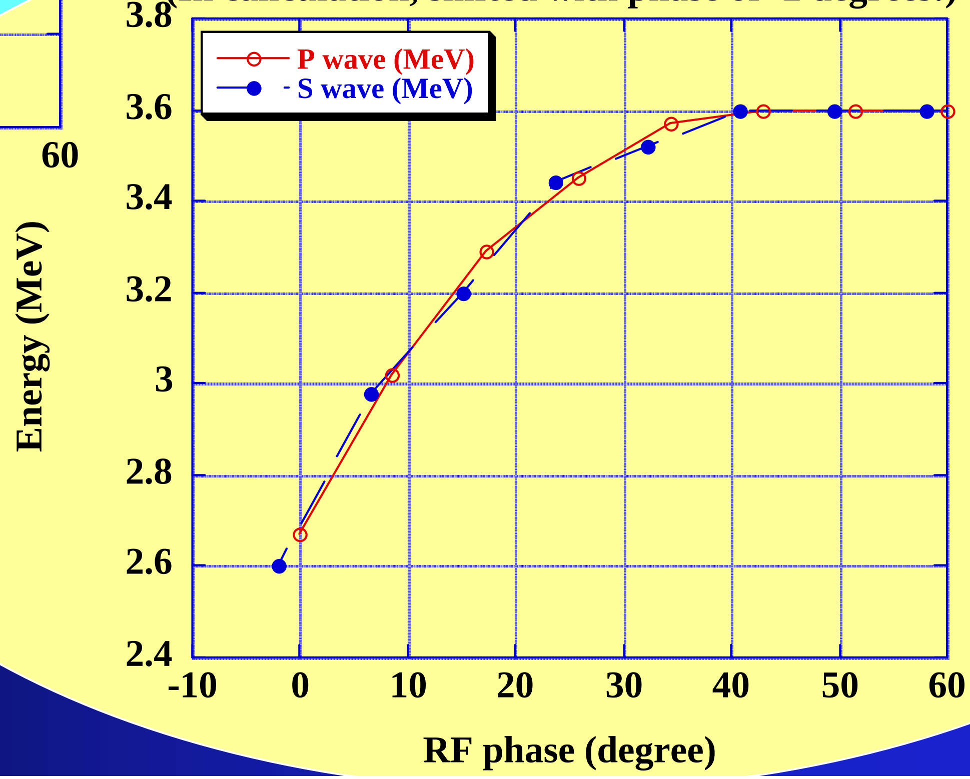
Shifted optical delay with a length of 4.5 mm

P-Pol was overlapped with S-Pol!
(In Measurement, shifted with Pulse Stacker micrometer)



Measured time deference between two beamlets (After shifted): 2ps

S-Pol was shifted to P-Pol!
(In caliculation, shifted with phase of -2 degrees!)



1~2ps deference coming from Timing Jitter ??

4. Optimization system of temporal profile

4-2. Candidates of SLM for UV-Laser pulse shaping

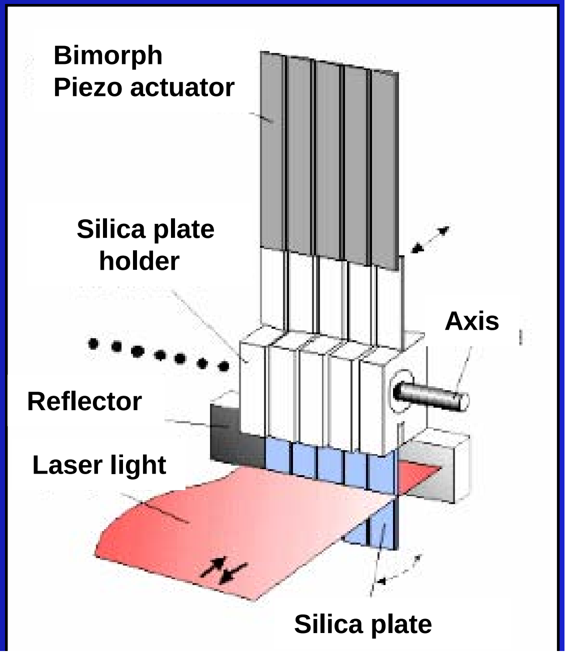
4-2-1. DAZZLER (Acousto-optics)

simultaneously and independently performing both spectral phase & amplitude of ultrafast laser pulses. (*FASTLITE*)

4-2-2. Fused-silica based SLM

Utilizing silica plates

- Directly shaping for UV-Laser
- Higher Laser power threshold



~ Computer-controllable silica plates complex ~

Simulated Annealing Algorisms (SA)

Pulse shape control with SiO_2-SLM

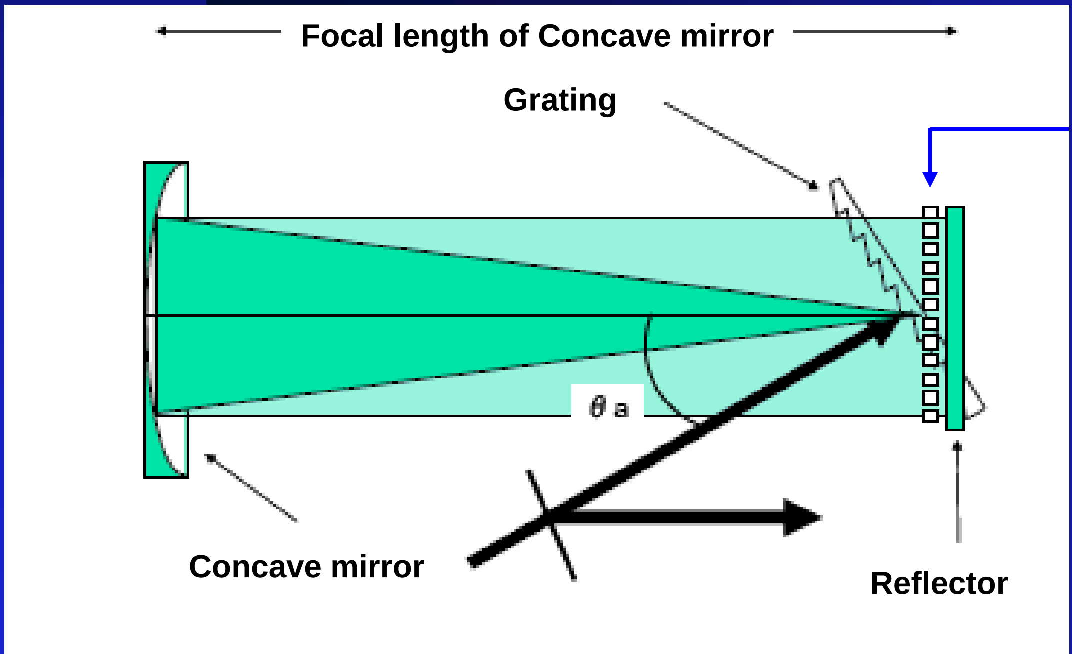
Short laser pulse

Grating — breaks a light pulse into a spectrum
(Transform time distribution to spatial distribution)

SLM — modulates phase distribution in spectrum

Grating — transforms the spectrum into a light pulse

Shaped laser pulse



Utilizing silica plate modulator

- Directly shaping for UV-Laser
- Higher Laser power threshold
  < 100 mJ/cm2

4. Optimization system of temporal profile

4-2-3. Results of Pulse Shaping with SLM

A) First test for computer-aided **SLM** was done in IR

→ **Rectangular Pulse (width range: 2-12 ps)**

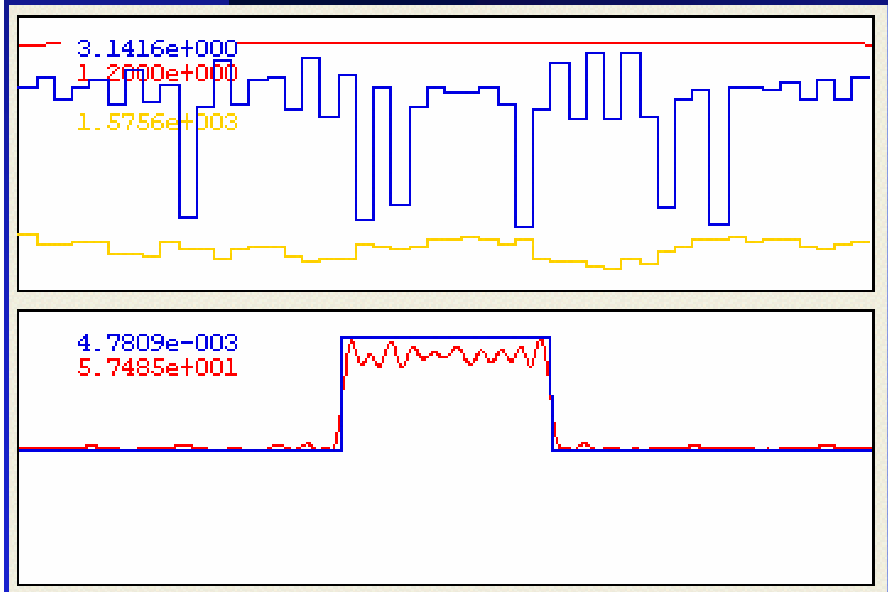
(rising-time: 800fs)

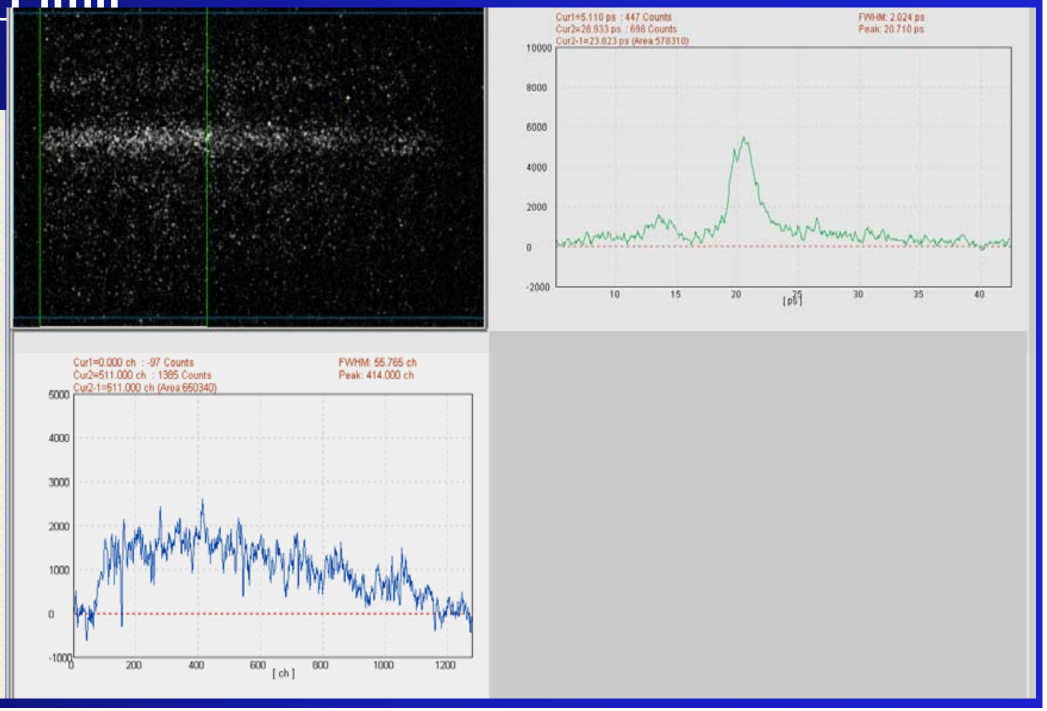
B) Computer-aided **SLM** in UV

→ **Size will be bigger (~5 times)**

Incident Pulse: Fourrier Transform Limit

Calculate Phase Spectra!



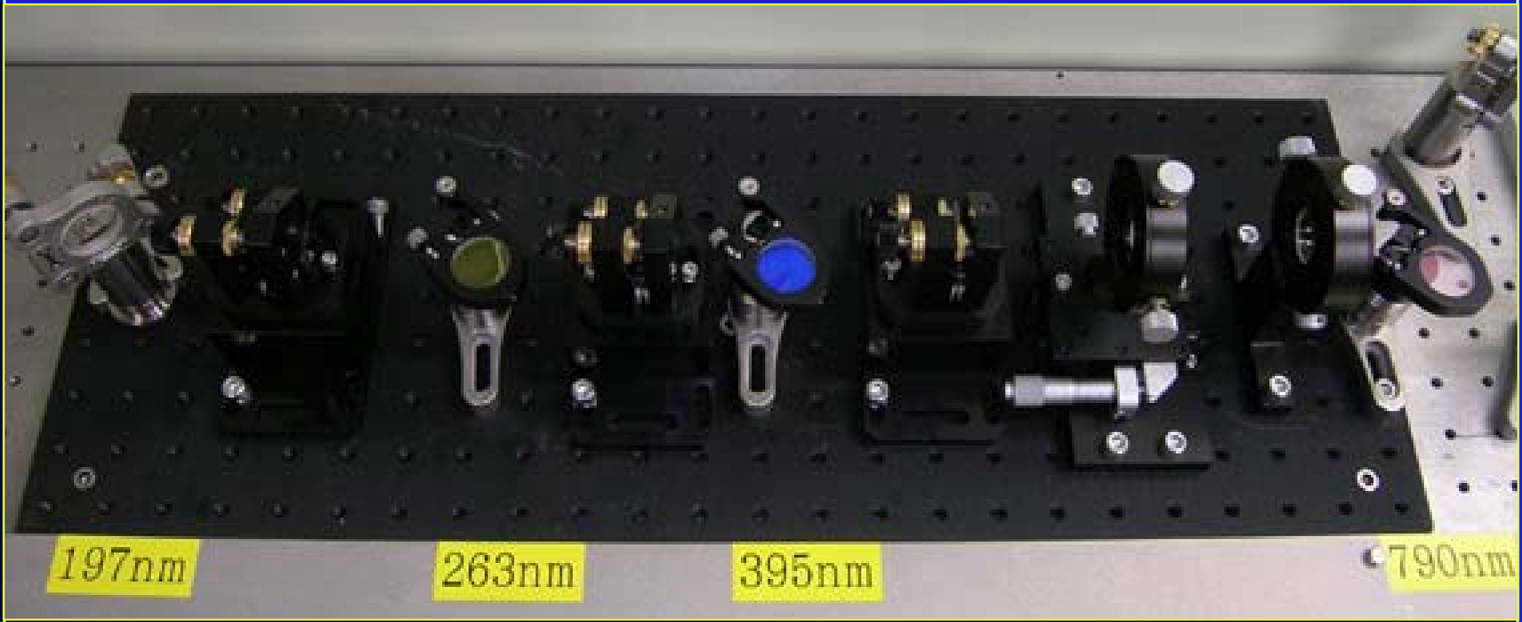


4. Optimization system of temporal profile

4-2-4. FHG(197nm), THG(263nm), SHG- System

After shaping with SLM,
Optimized UV-Laser pulse is available !

Feedback system with streak camera &
Beam transport are under construction.



5. Summary and future plan

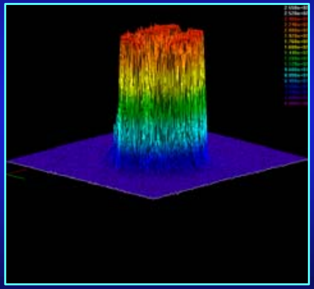
~ Spatial Shaping ~

A. Characterics of Methods of shaping Spatial profile

Limit of Wave Length : MLA < DM
perfect Ideal Profile : DM > MLA
Pointing Adjustability: DM > MLA
Cost ($\$10^3 < \$10^5$) : MLA < DM

B. When Spatial Profile was improved, Emittance was reduced down to $2.0\ \pi$ mm mrad. (Microlens Array)
~ Before installation of Homogenizer, $6.0\ \pi$ mm mrad. ~

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



~ However, it takes 1 hour to optimize.

D. In our future plan, compensating inhomogeneous QE-distribution with DM (Spatial) & e-profile monitor

5. Summary and future plan

~ Temporal Pulse Shaping ~

E. Characterics of Methods of shaping Temporal profile

Limit of Wave Length : DAZZLER < Silica < UV-PS

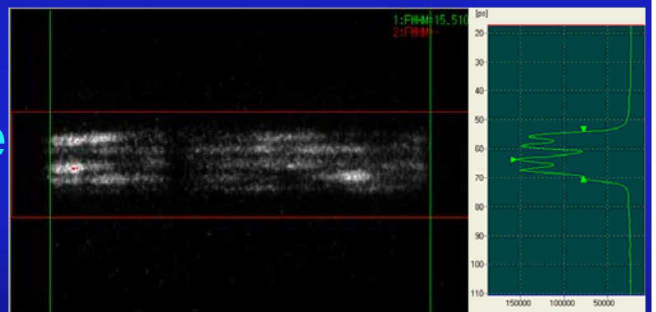
Perfect Rectenglar Pulse : DAZZLER ~ UV-PS > Silica

Comactness (10cm > 2~5 m) : DAZZLER > Silica

Cost ($$10^4$ < $$10^5$) : UV-PS < Silica ~ DAZZLER

F. Square pulse generation with UV-pulse stacker (UV-PS) was successful at THG (263 nm)!

Square Pulse: ~2 - 20 ps; Rising-time: ~ 700 fs



~ It is possible to generate VUV-pulse (197nm) for diamond cathode !! ~

~ Now, optical-contact-type polarized splittercube material available in UV! Our kit of UV-PS is commercially available. ~

5. Summary and future plan

~ Temporal Pulse Shaping ~

G. Automatically shaping Temporal Profile with fused-silica based SLM was successful in IR after MP-Amp!

Square Pulse: 2-12 ps; Rising-time: 800 fs

~ It is possible to shape UV-pulse, however size is larger. ~

~ If the crystal material available in UV region, DAZZLER is the most reliable. ~

H. In our future plan, compensating any kind of distortion with SLM (Temporal) & e-bunch monitor (or Energy analyzer)

~ Need collaboration with other fields ~

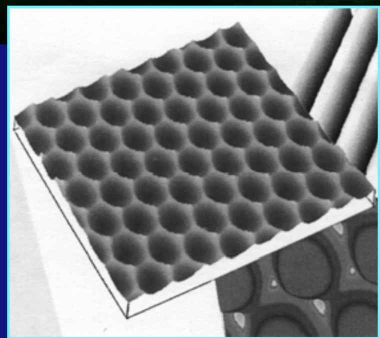
I. In our future plan, compensating any kind of distortion & inhomogenities on 3D- electron bunch with DM (Spatial) & SLM (Temporal) & e-bunch monitor !!!

However, do not forget to investigate interesting physics on phenomena of generating electron bunch just after laser incidence, just on the photocathode !!!!!

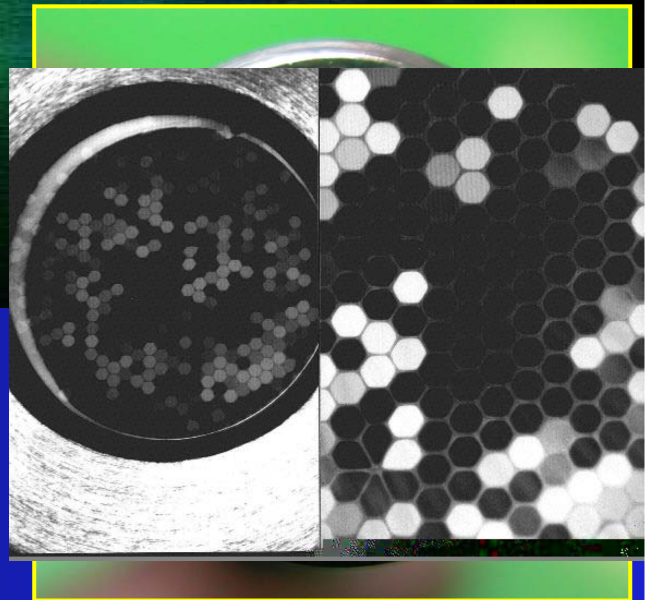
A. Both profiles shaping with Fiber Bundle

~ FB can 3D-shape the UV-pulse & make easy to transport ~

Cable Strand



Microlens Array

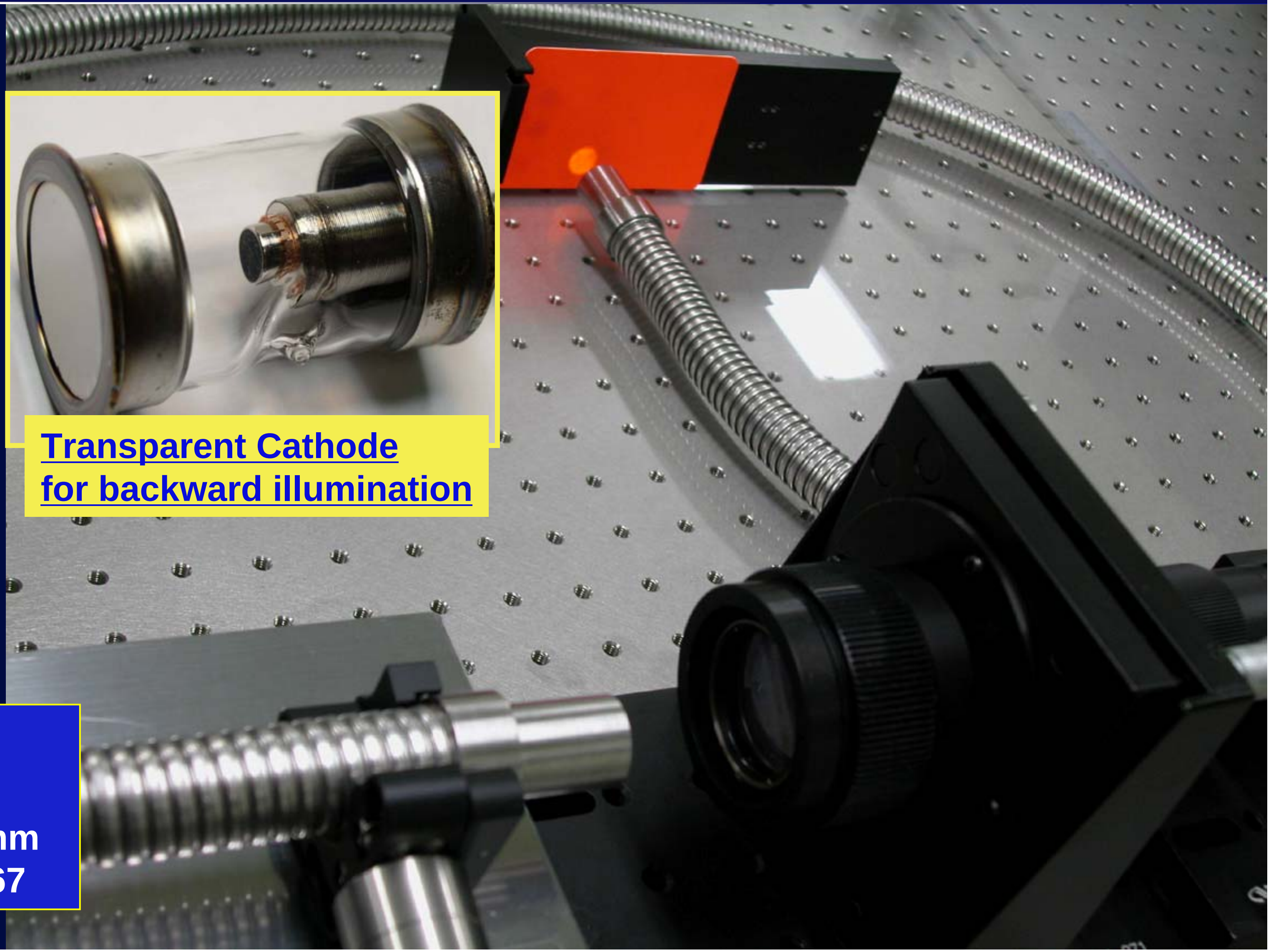


Silica Fiber Bundle

A. Both profiles shaping with Fiber Bundle

~ Transparent Cathode with Fiber Bundle ~

Pulse Stacking with 2,000 different Optical Passes



Transparent Cathode for backward illumination

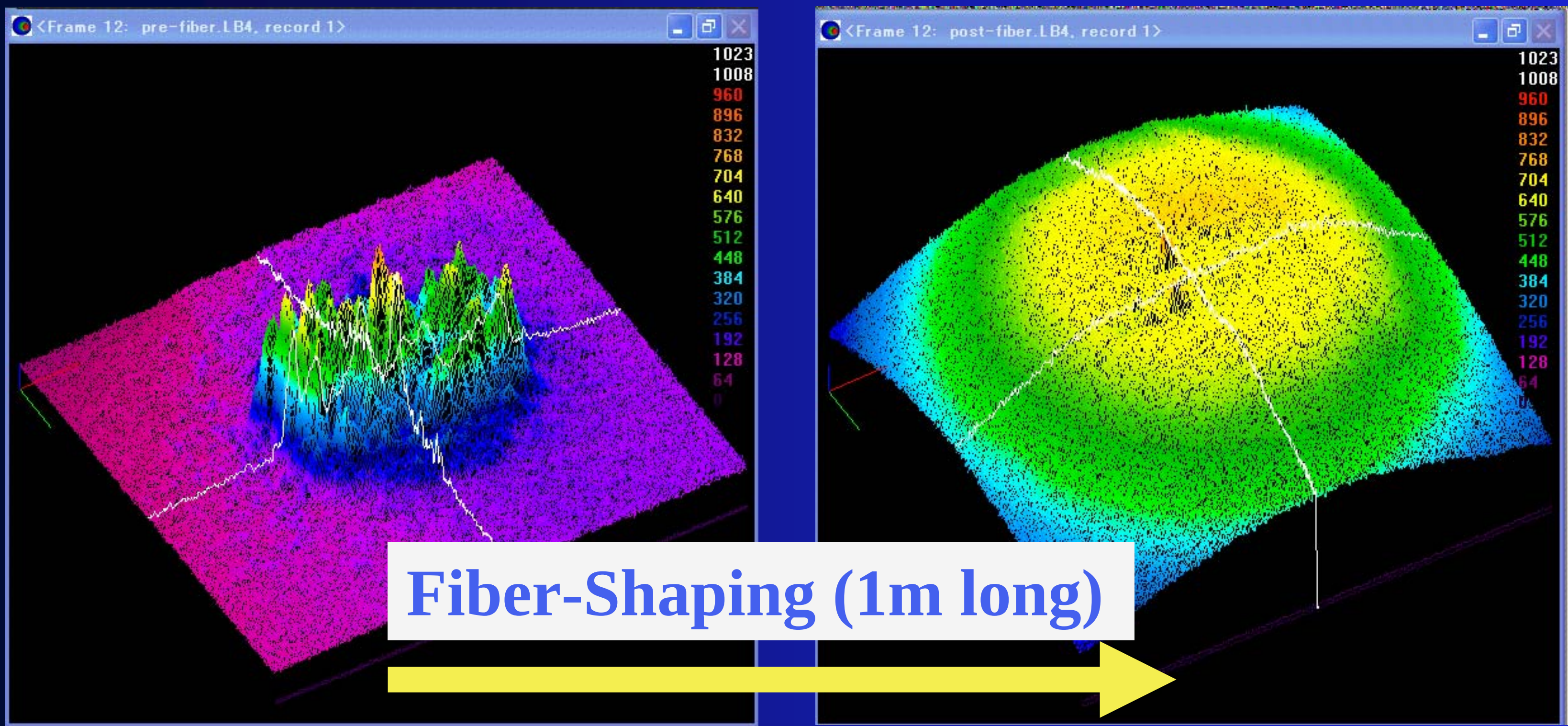
Fiber Bundle:

Length: 2.0 m
Bundle size : 12 mm
No. of Fibers : 1967

A. Both profiles shaping with Fiber Bundle

1. Results of spatial profiles with shaping

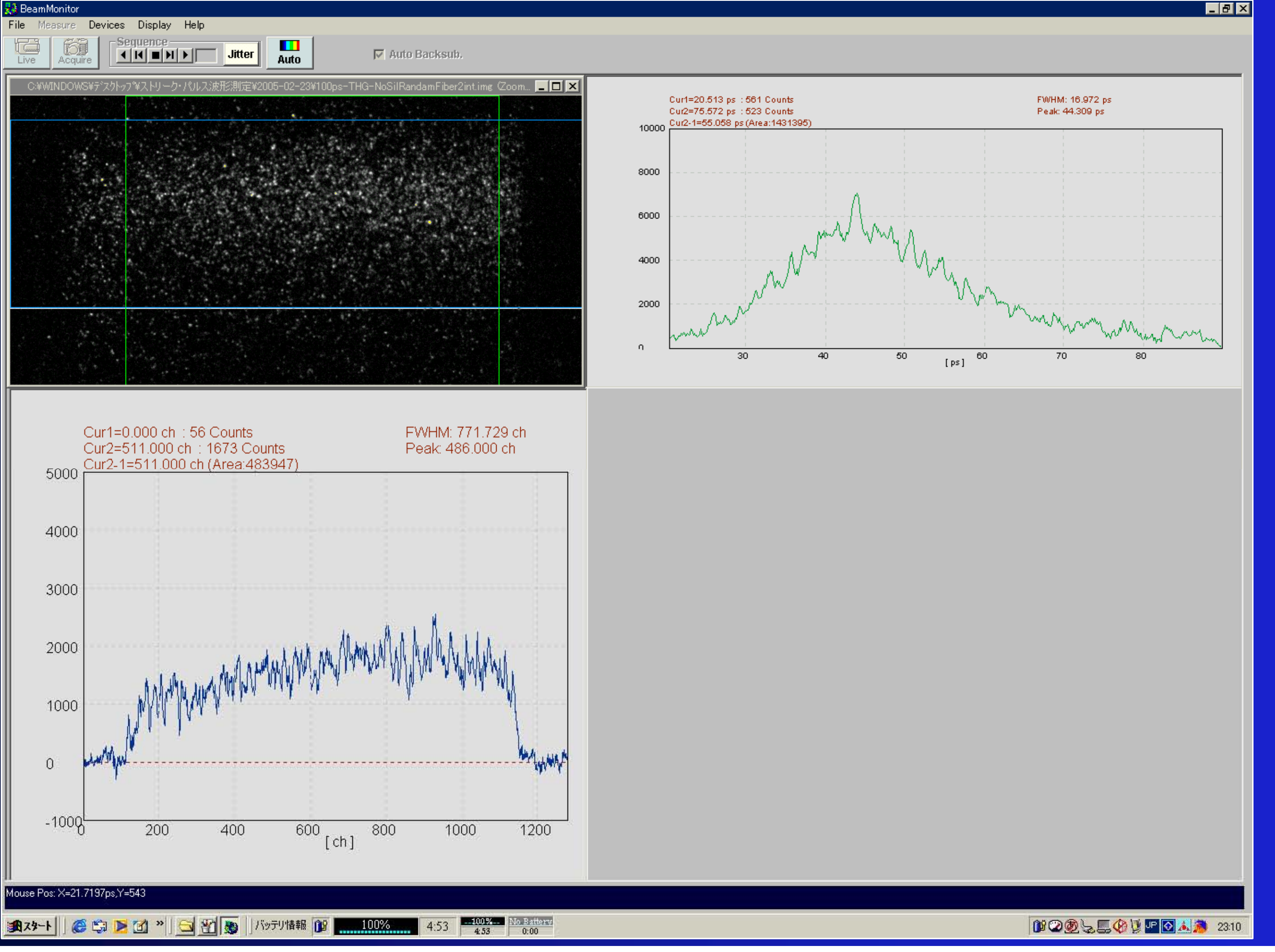
- Spatially homogenizing is very strong with FB
  - ⇨ **Any kind of bad profile can be corrected!**
- Pulse shaping & stretching with FB is **pulse-stacking**
  - ⇨ **Depend on the length and mapping of FB**



A. Both profiles shaping with Fiber Bundle

2. Results of temporal profiles with shaping

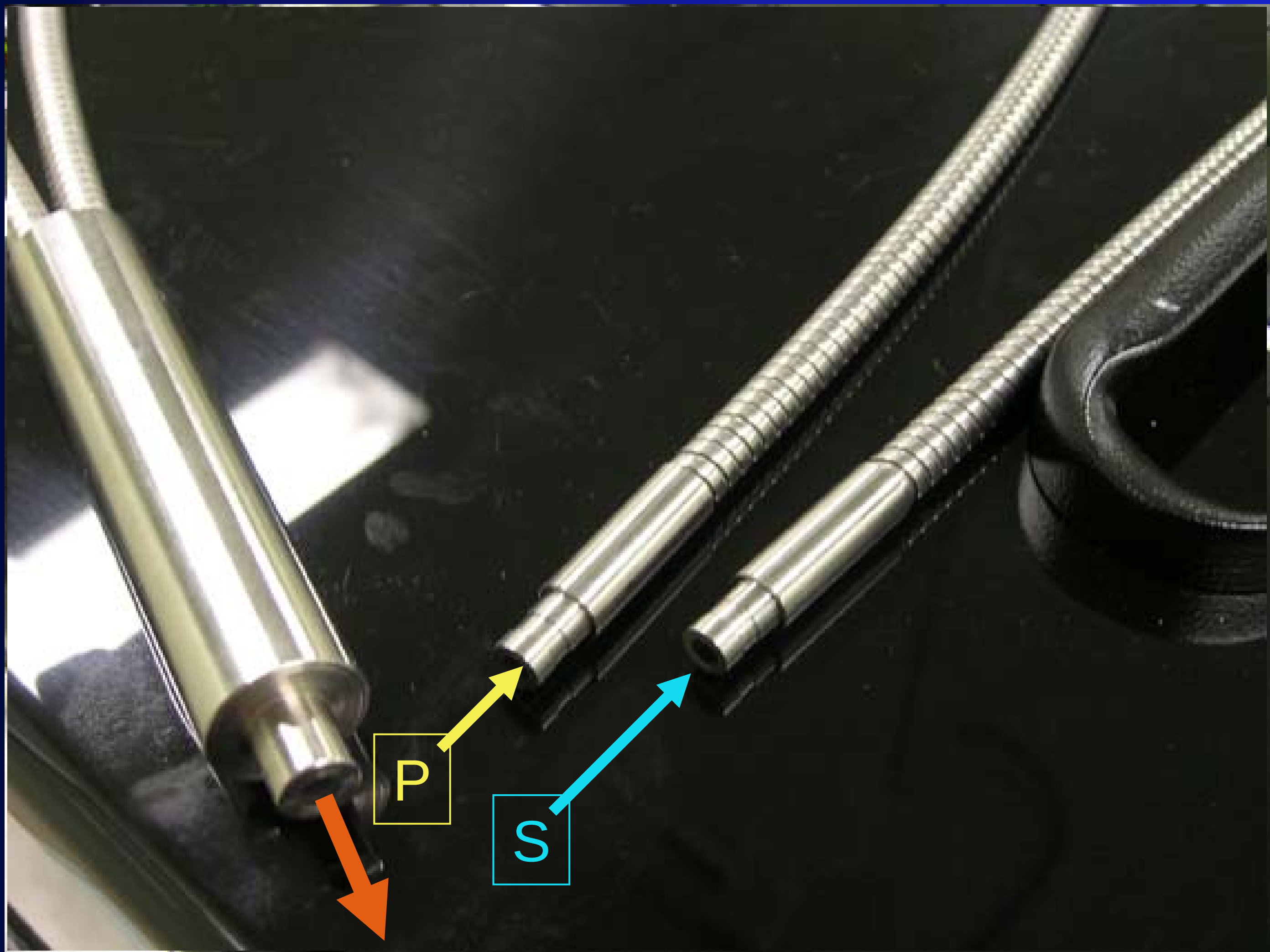
~ Pulse shaping result due to mainly Pulse Staking effect ~



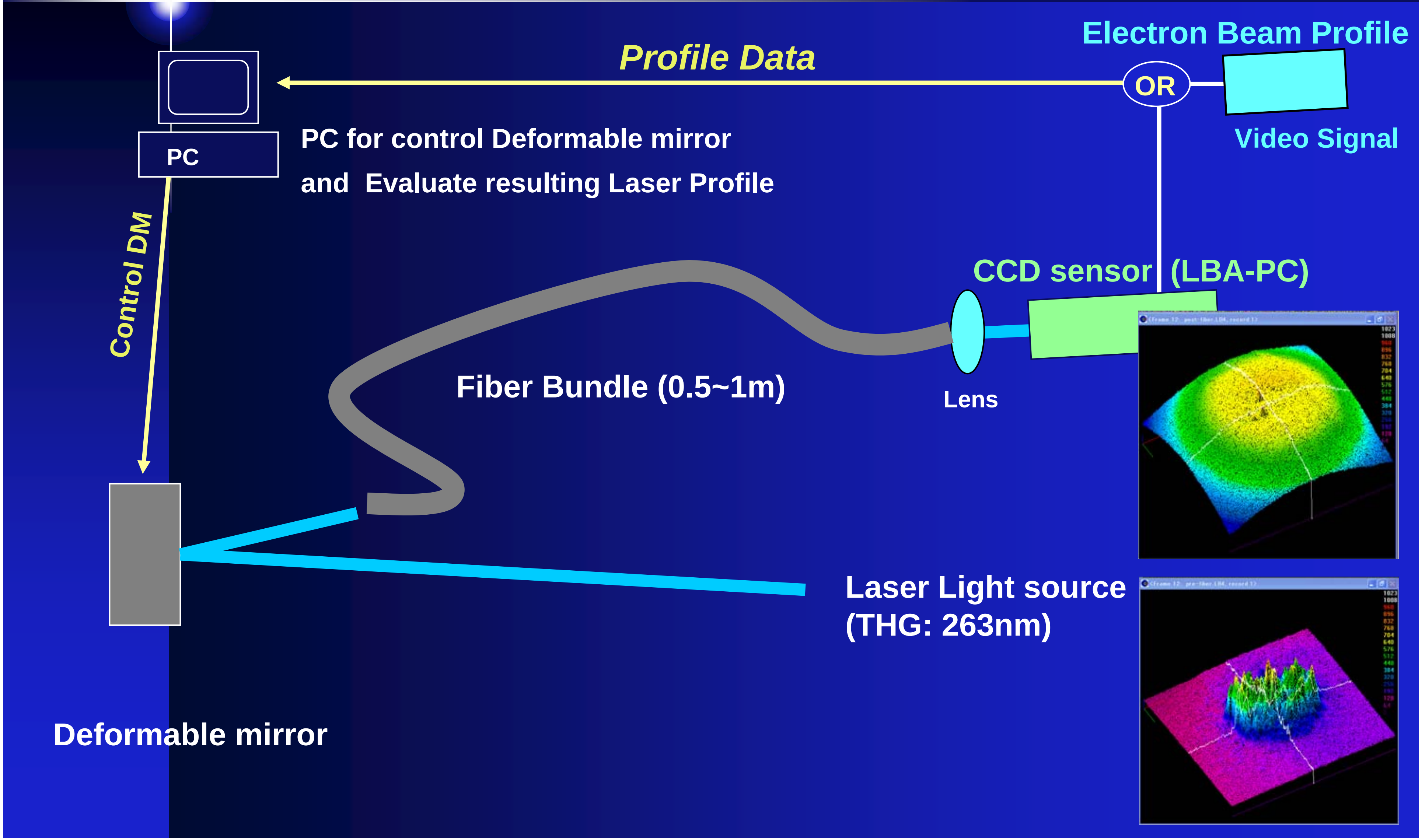
A. Both profiles shaping with Fiber Bundle

3. Eliminating interference of laser pulse

~ The neighbor beamlets have orthogonal polarizations (S & P) ~



Closed Control System for Fiber Bundle with computer-aided Deformable mirror



A. 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.