Development of automatically optimizing system of both spatial and temporal beam shaping for UV-laser pulse

Hiromistu Tomizawa

Accelerator Division,
Japan Synchrotron Radiation Research Institute (SPring-8)

1. Introduction ~ Present status of UV-light source ~
2. Motivation for beam quality control
3. Optimization system of spatial profile
   ～ Automation with DM + GA ～
4. Optimization system of temporal profile
   ～ Automation with SiO_2-SLM + SA ～
5. Summary and future plan

1. Introduction

1-1. Highly qualified Laser light source

1. For generation of the lower emittance beam
   ⇨ Optimization of laser 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
   ⇨ Stabilization of total laser system
   through environmental control

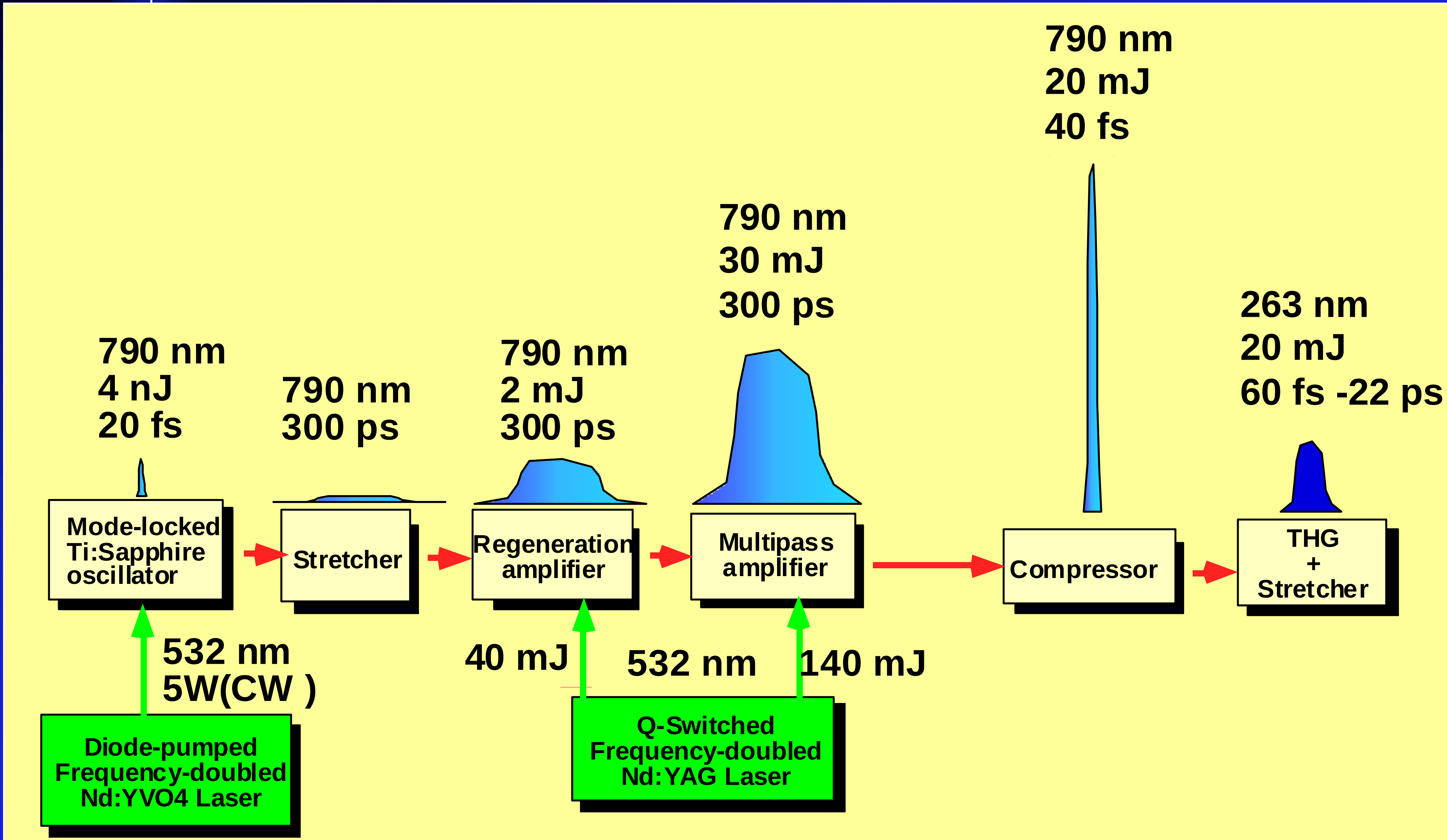
In principle,
Environmental control!

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

1. Introduction

1-2. Laser System Configuration

~ Femto second TW- Ti:Sa Laser System ~



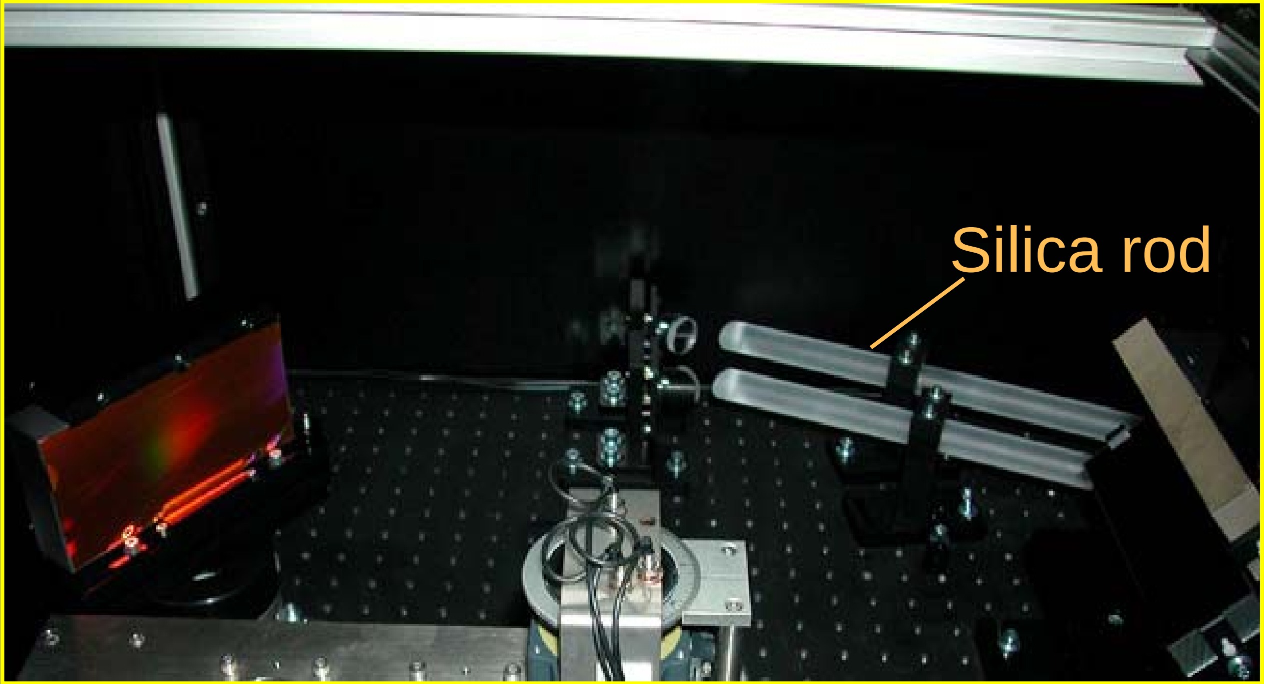
THG Pulse Silica-rod Stretcher

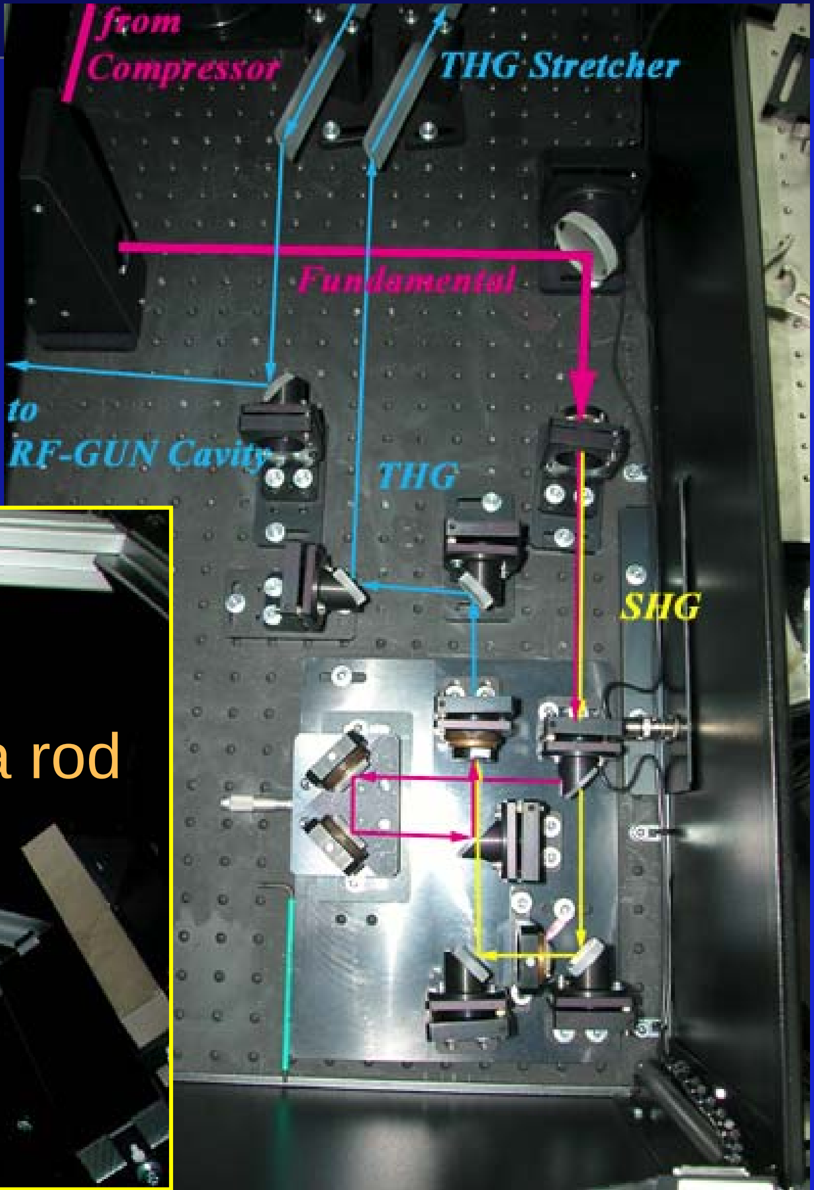
~ utilizing the dispersion in Silica ~

Possible: Pulse Duration

Impossible: ideal Pulse shape

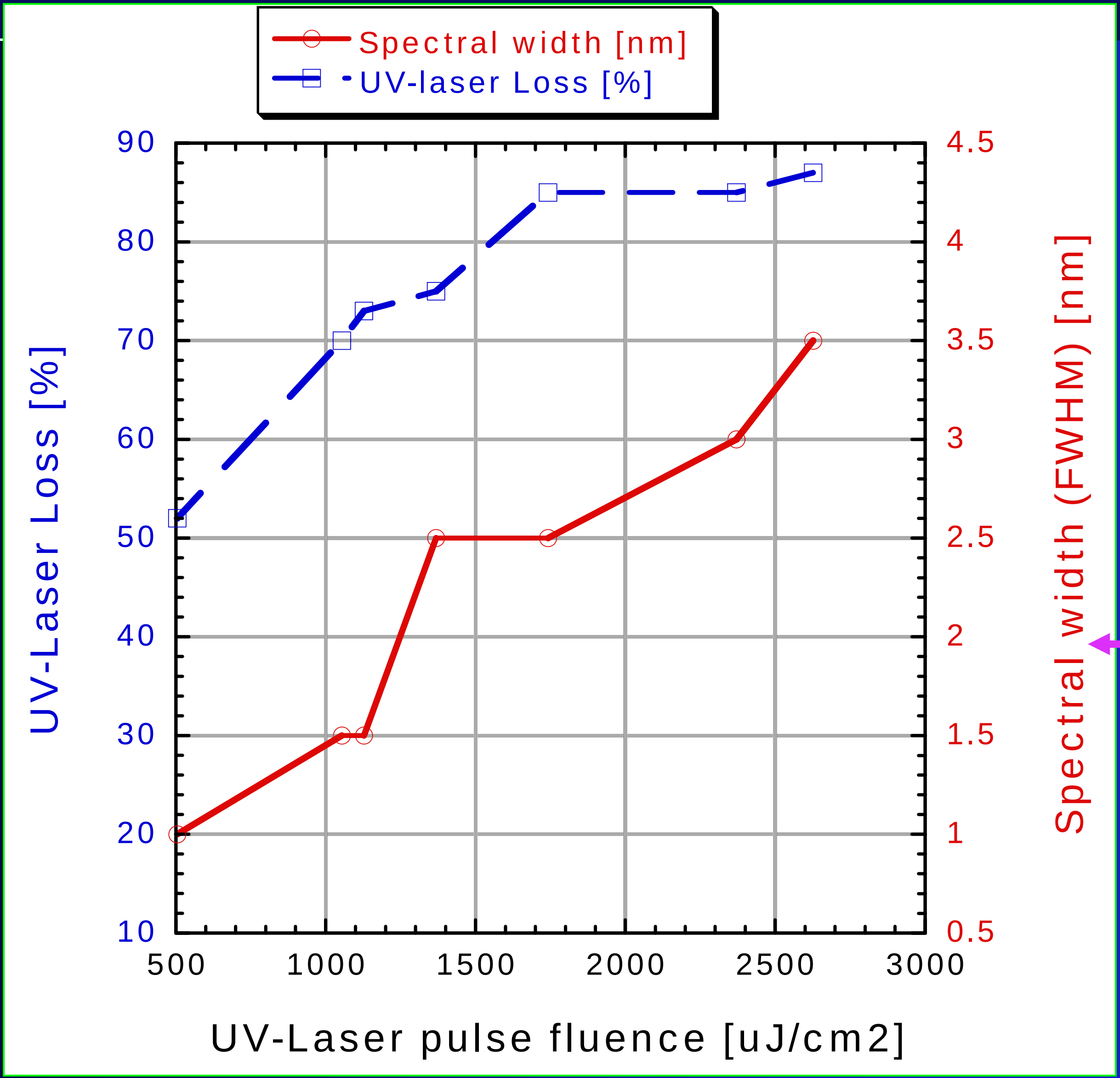
~ 90 % pulse energy loss at most ~





Pulse stretching effect in Silica rods

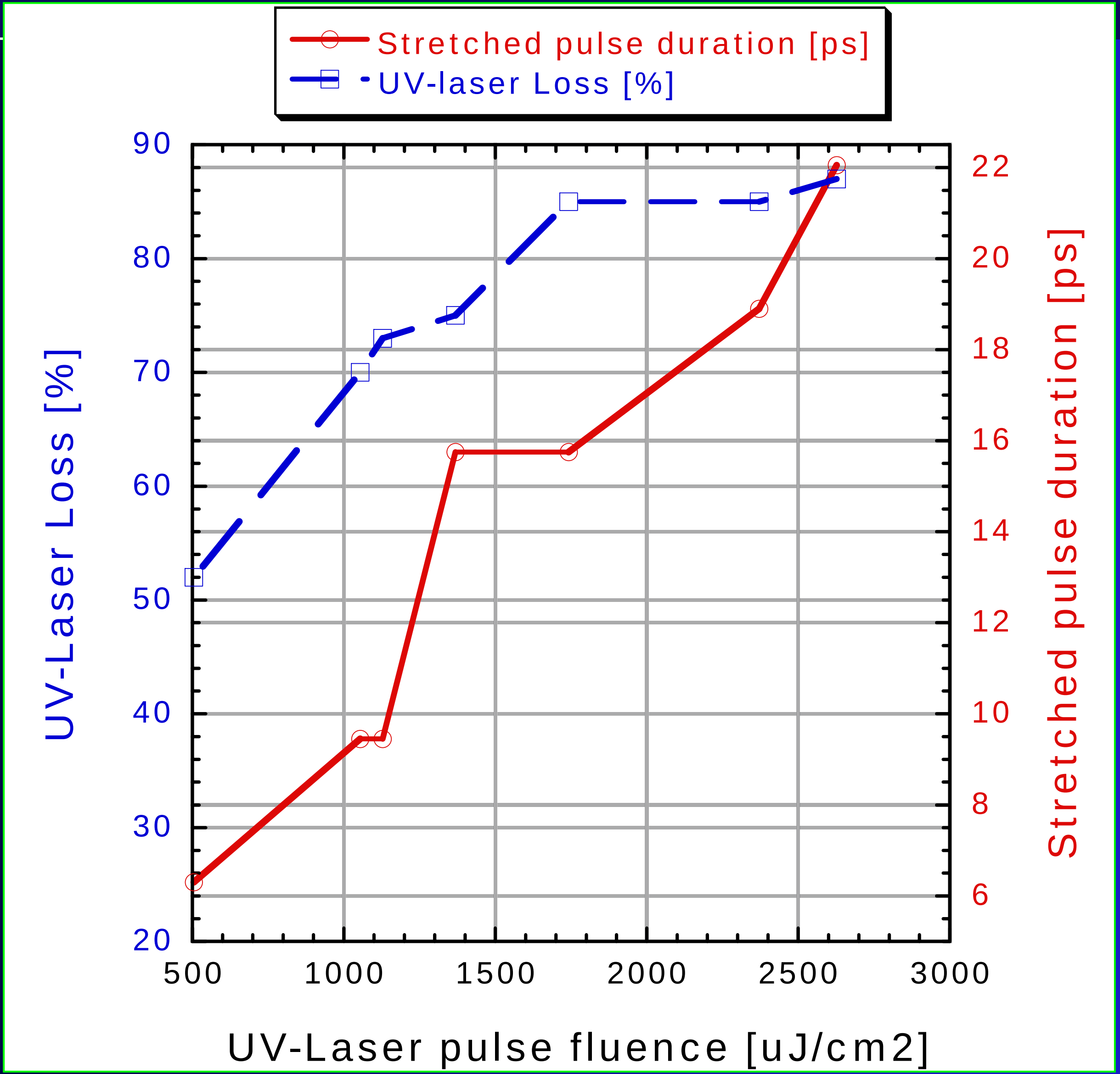
in Spectrum



before ST
2 nm

Pulse stretching effect in Silica rods

in Pulse Duration

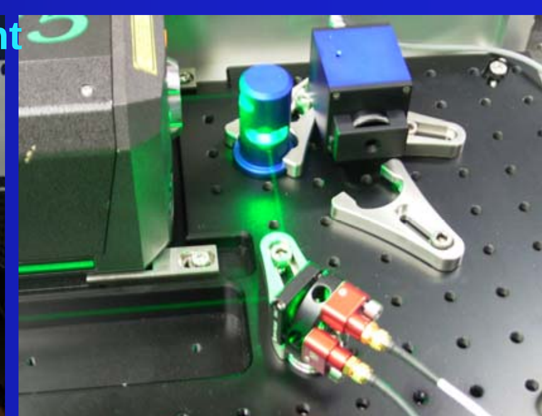


1. Introduction

1-3. Present status of Laser System in humidity-controlled clean room

Laser System after passive stabilization

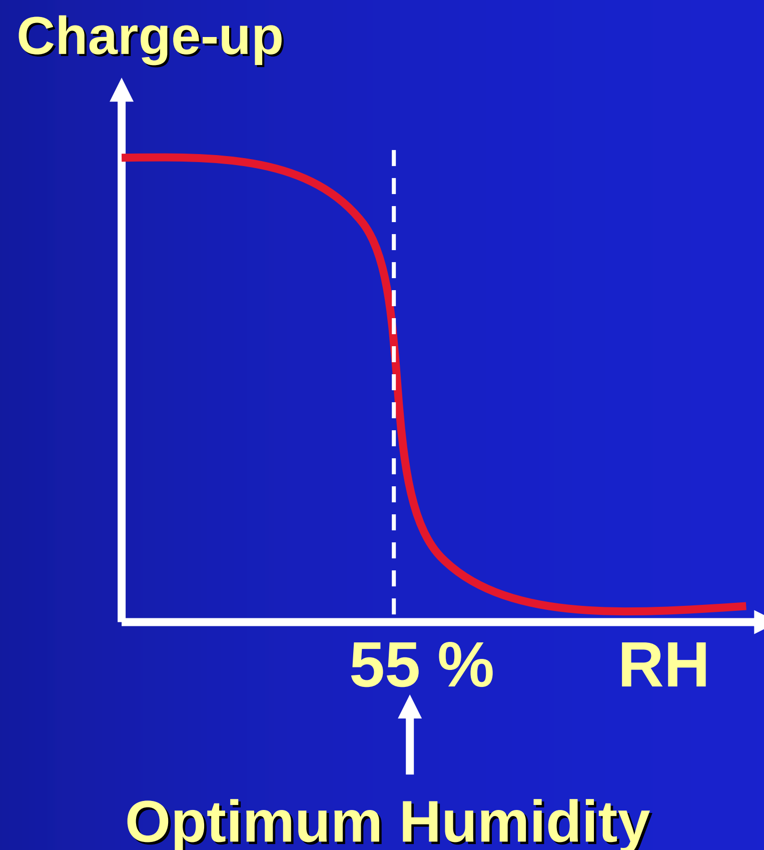
New Oscillator with auto alignment



Humidification for avoiding charge-up

Environmental test clean room

Constant Temperature & Humidity



(Under Construction and Laser Replacement: 2002 ~2004)

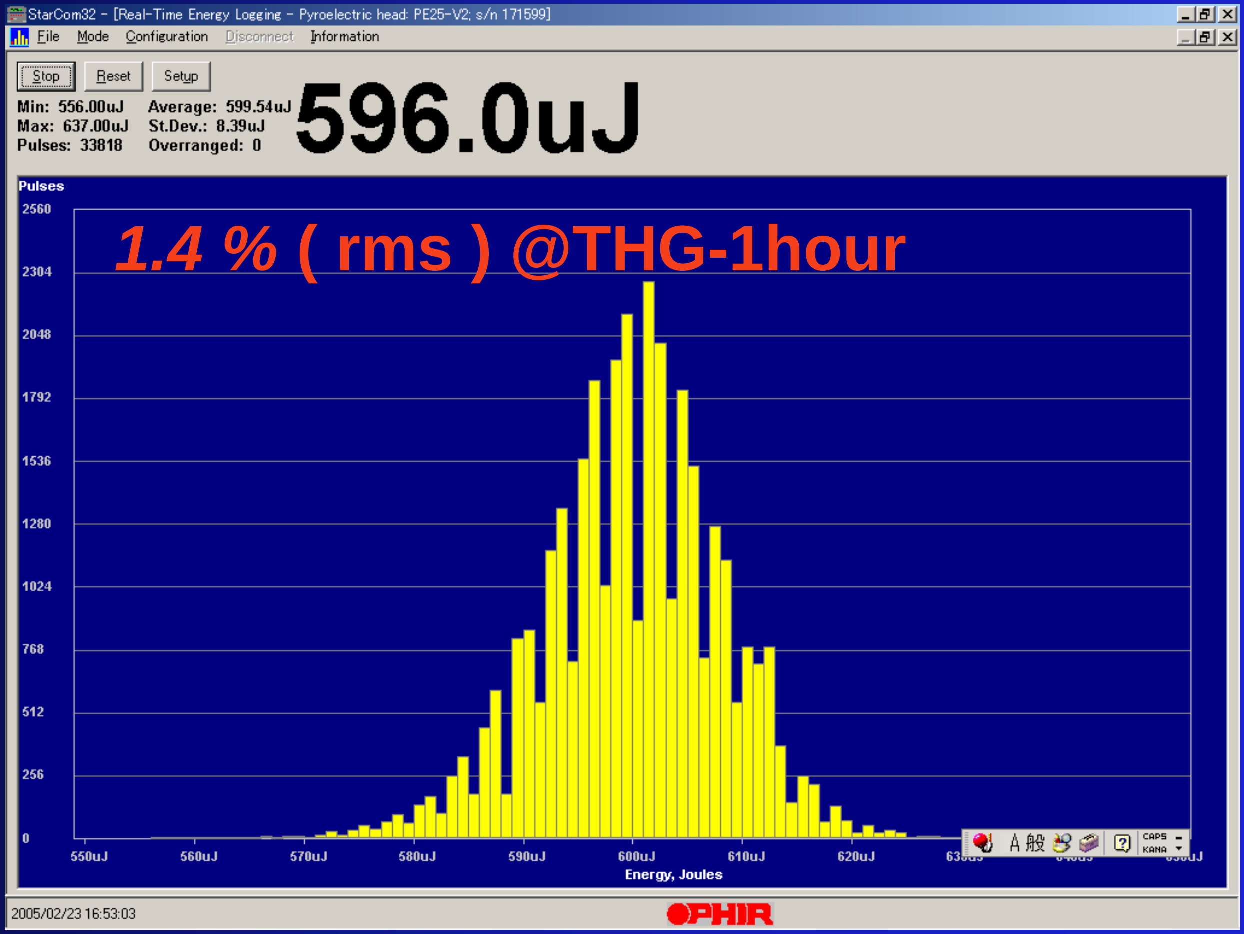
The present status of stability of UV-Laser

Present UV-laser stability:

0.2 ~ 0.3 % (rms) @ Fundamental

Long Term: 2 – 3 Weeks continuously

With new Oscillator, it will be 2 months.

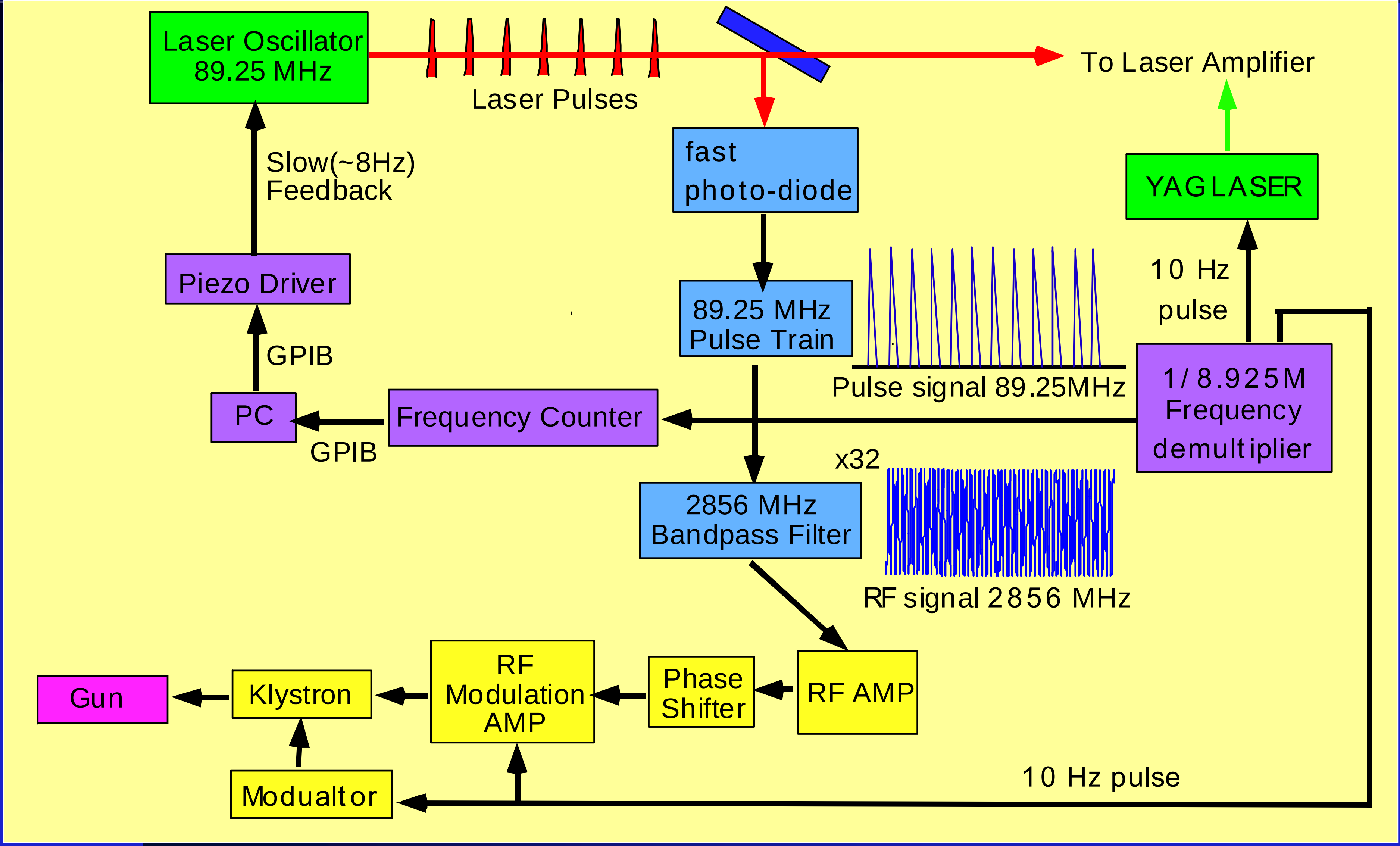


After Passive control

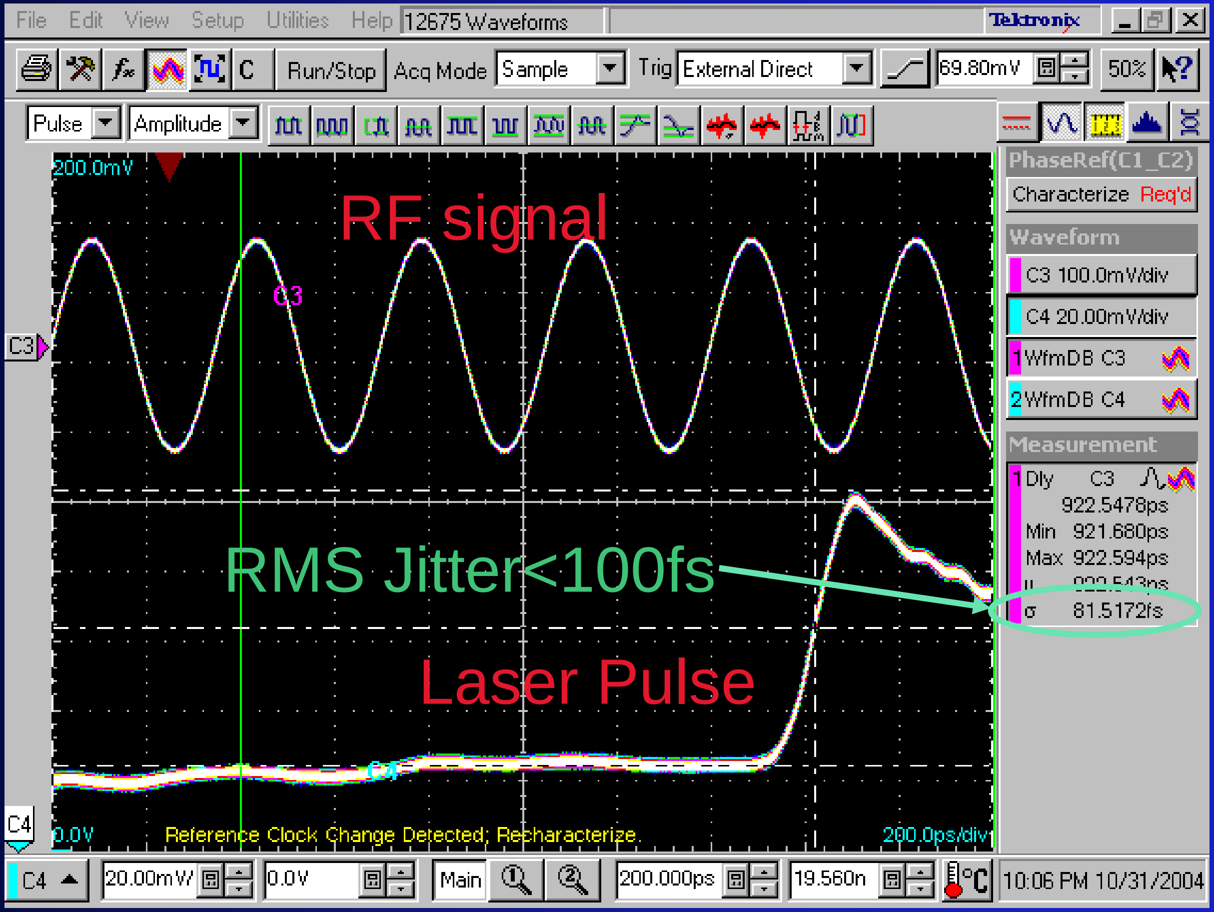
5 ~ 10 % (rms) → *0.95 ~ 1.4 %* (rms)

1. Introduction

1-4. Laser & RF Synchronization



Short Time Jitter Measurement

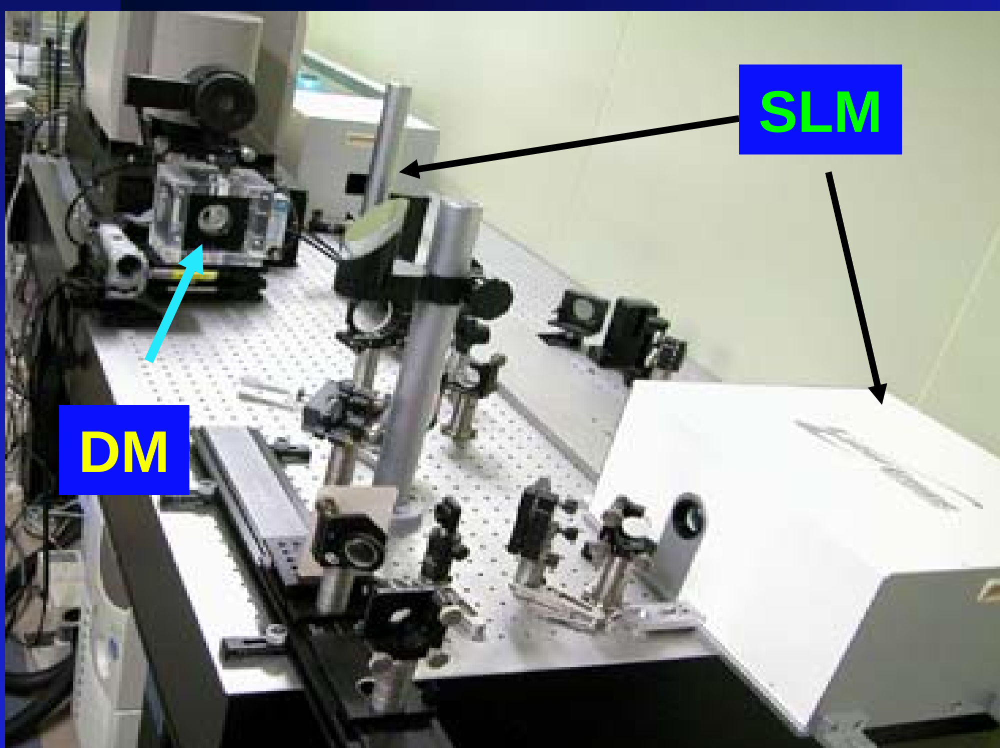


Time delay between RF signal & Laser pulse measured with Tektronix TDS8200 Sampling Oscilloscope

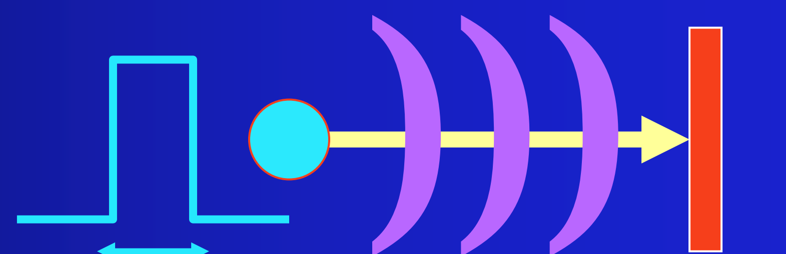
1. Introduction

1-5. Automatic Laser Beam Quality control syste

- Computer-aided **SLM (Spatial Light Modulator)**
  ⇨ **Rectangular Pulse shaping (adjustable)**
- Computer-aided **DM (Deformable mirror)**
  ⇨ **Flattop spatial profile (adjustable)**



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

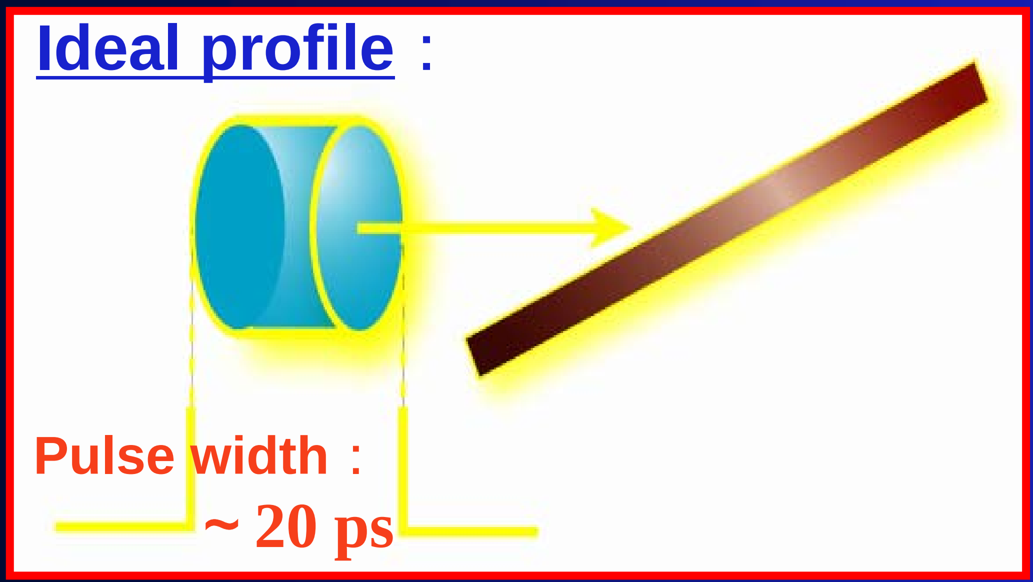


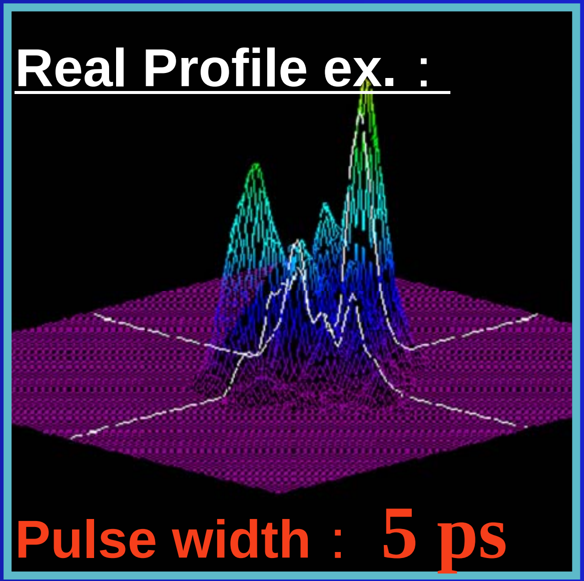
2 ~ 20 ps Fundamental
2 ~ 20 ps THG (263 nm)

2. Motivation for beam quality control

2-1. Necessity of improvement of laser profiles

Spatial and Temporal Profiles ⇨ Shaping Methods





Beam Quality Control →

- Temporal Profile
- Spatial Profile
- Wave Front

2. Motivation for beam quality control

2-2. 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!

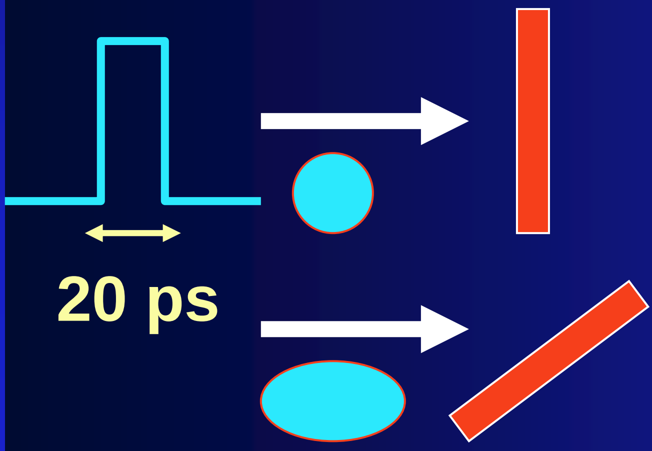
2. Motivation for beam quality control

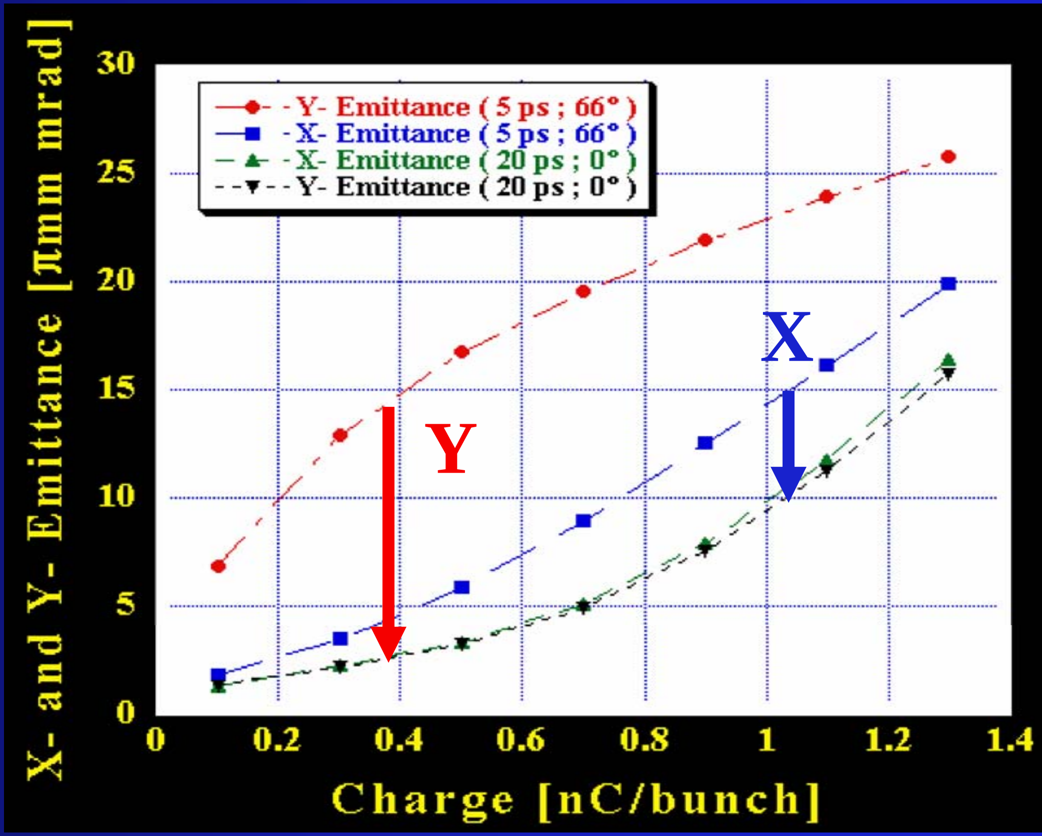
2-3. Influence of laser pulse shape and wave fr

- Square Pulse with the optimal width ~ 20 ps
- Wave front of laser pulse should reach at the same time to the cathode surface!

Normal or

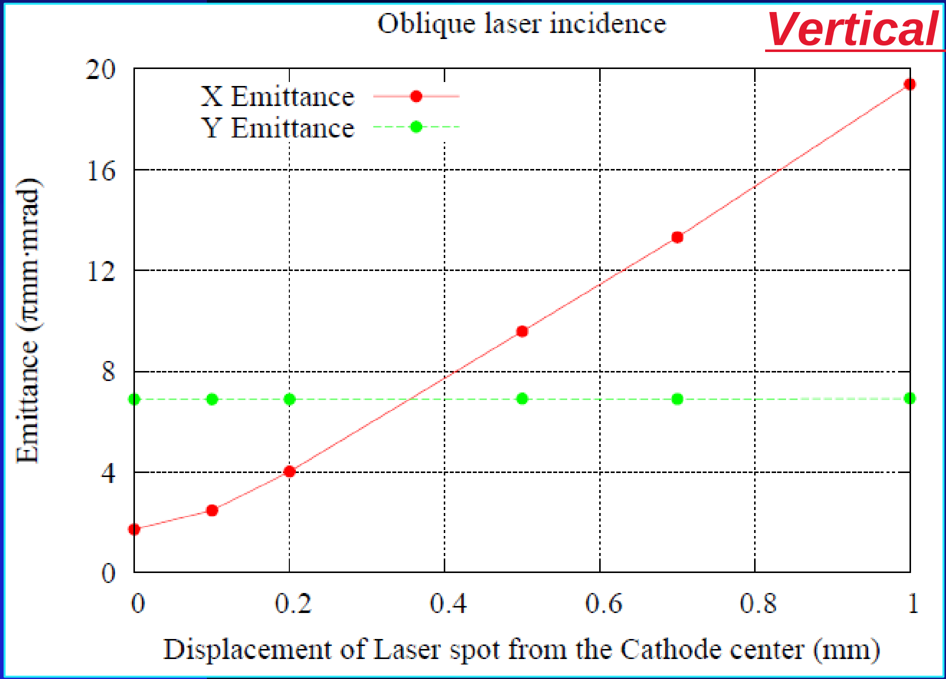
⇨ Backward Incidence!



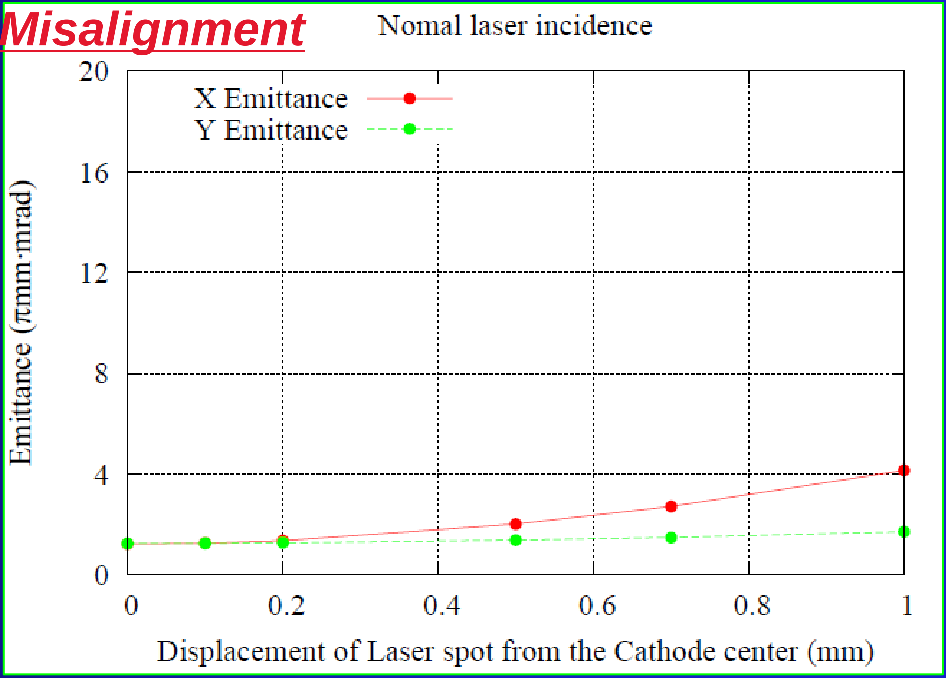


2-4. Influence of spatial profile & misalignment

- 0.1-mm misalignment makes twice emittance growth in the case of the oblique incidence
  - ⇨ **Our emittace improvement (The space charge effect is not dominant.)**
- Nomal incidence makes more tolerant for misalignment.
  - ⇨ **Optimum profile for space charge dominant region. (Automatically Optimizing with Adaptive Optics.)**



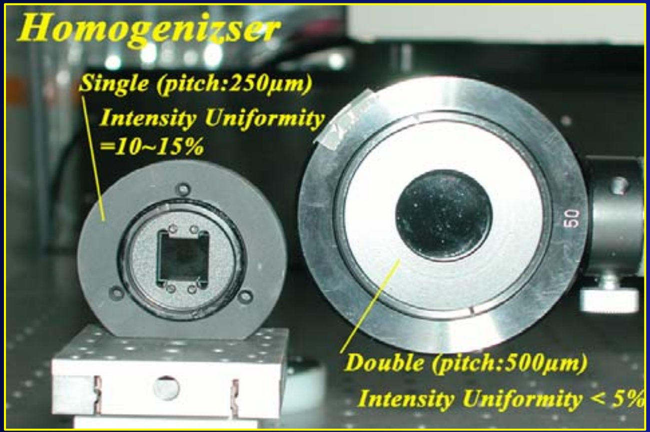
Vertical Misalignment

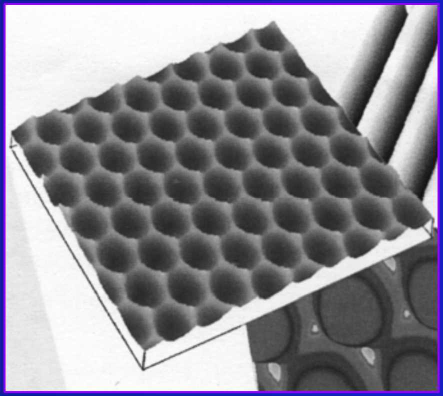


3 . Optimization system of spatial profile

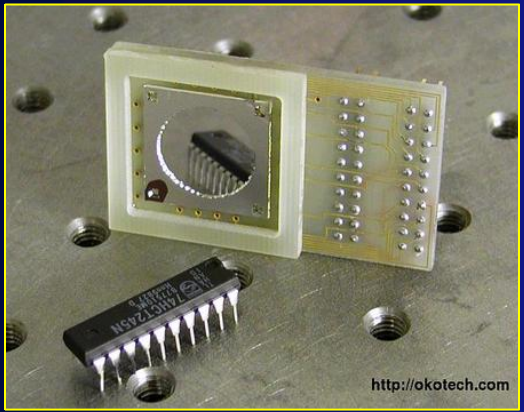
~ Microlens array (MLA) and Deformable Mirror (DM) ~

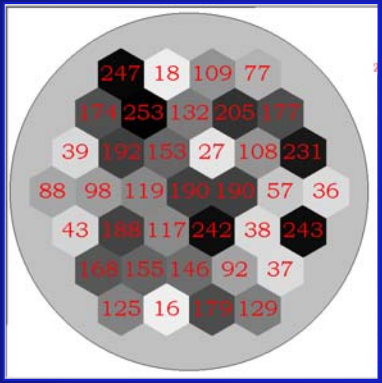
3 - 1 . Spatial profile shaping with Microlens Array





3 - 2 . Spatial profile shaping with Deformable Mirr





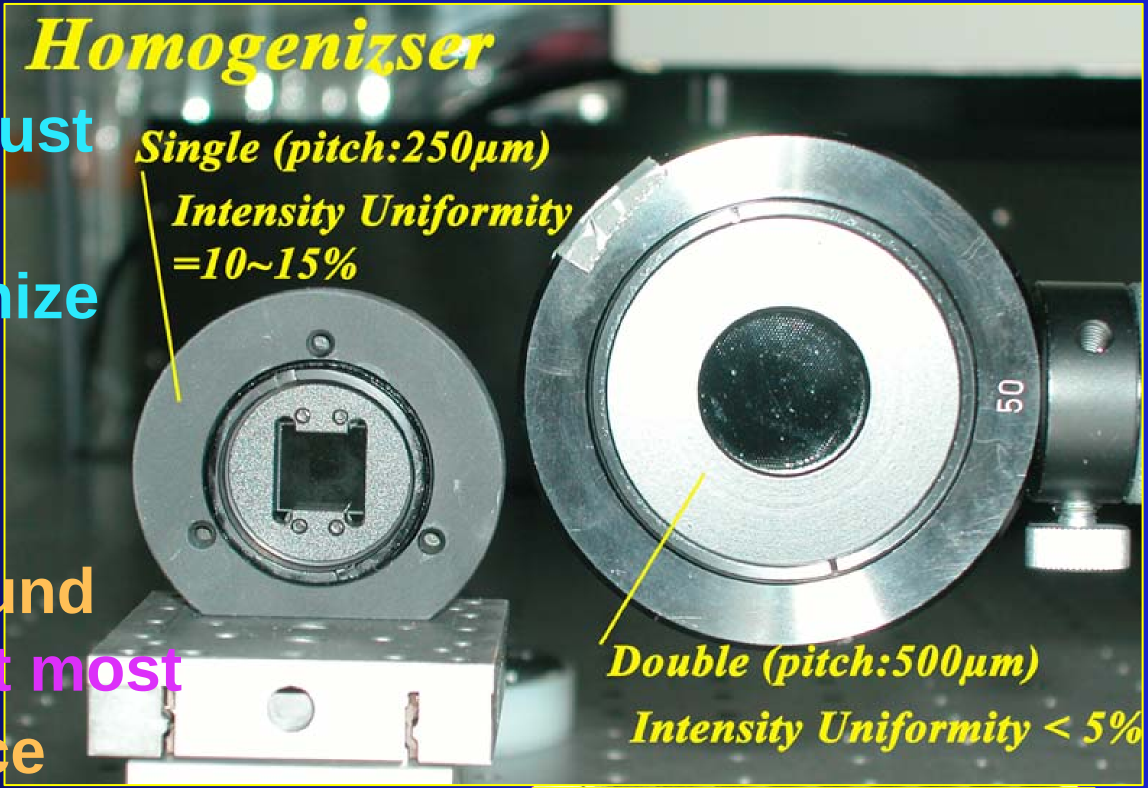
+ **Genetic Algorithms**

3 - 1. Spatial profile shaping with MLA

3 - 1 - 1. Microlens Array : effective & adjusta combination with combination with Len

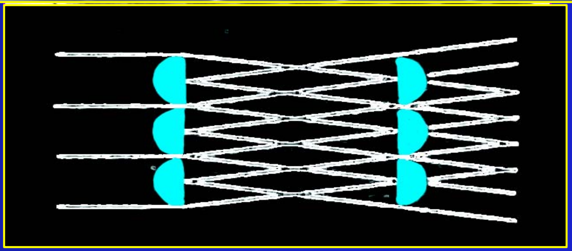
Merit:

- 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

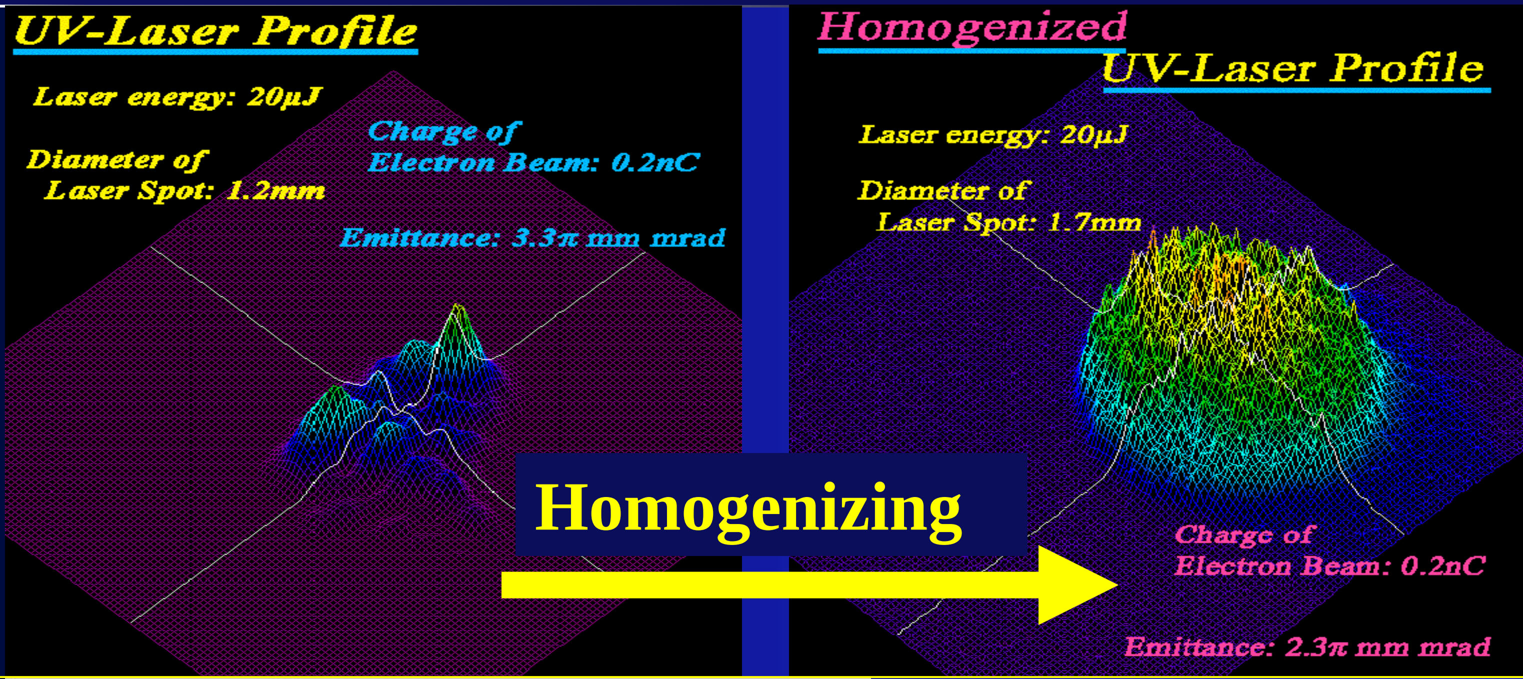


Note that: pitch >20 μm, pulse width >500 fs

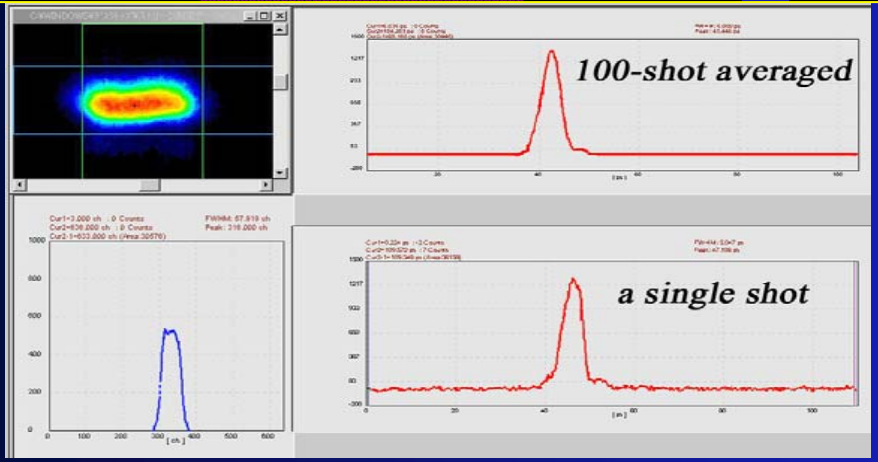
3 - 1. Spatial profile shaping with MLA

3 - 1 - 2 . Results of laser profiles with shaping

Spatial:



Temporal:



Spot size: 2.0 mm

Pulse width: 5 ps

(45-cm Fused Silica ×2)

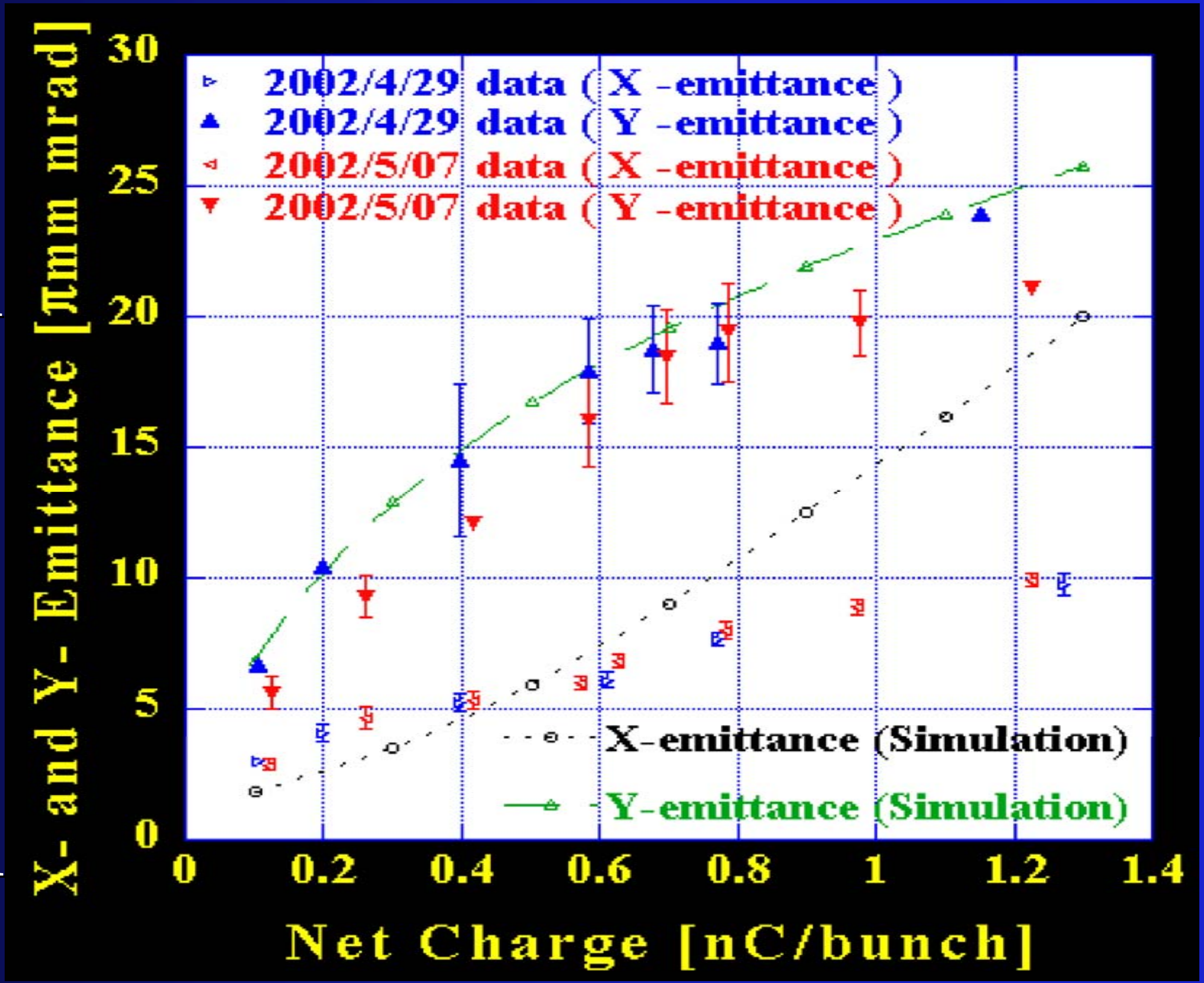
3-1. Spatial profile shaping with MLA
3-1-3. Results of emittance measurement

(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) ~

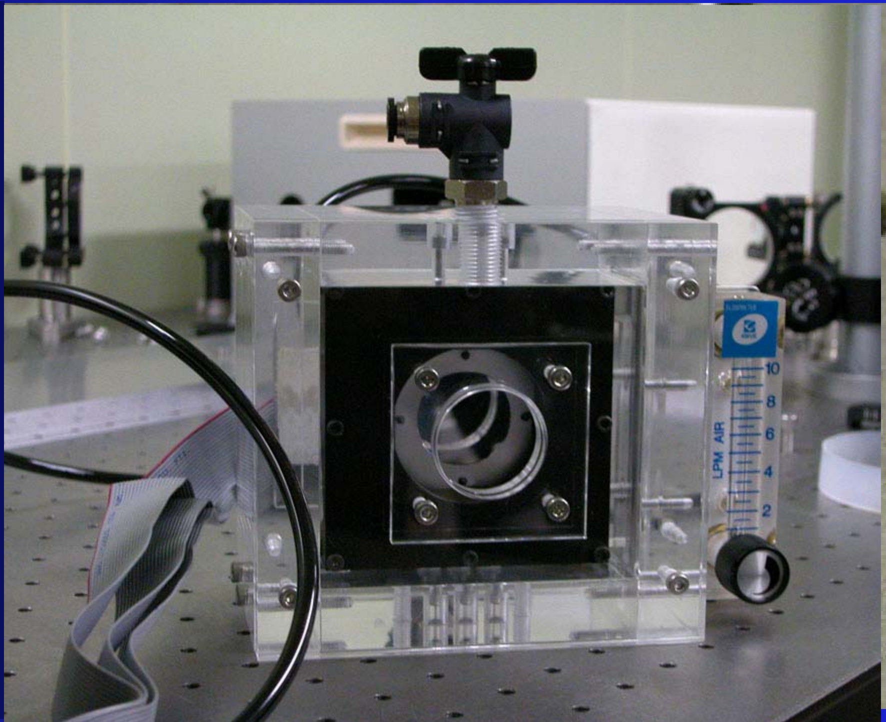
Merit: *adjustable and actively controllable!!*

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)



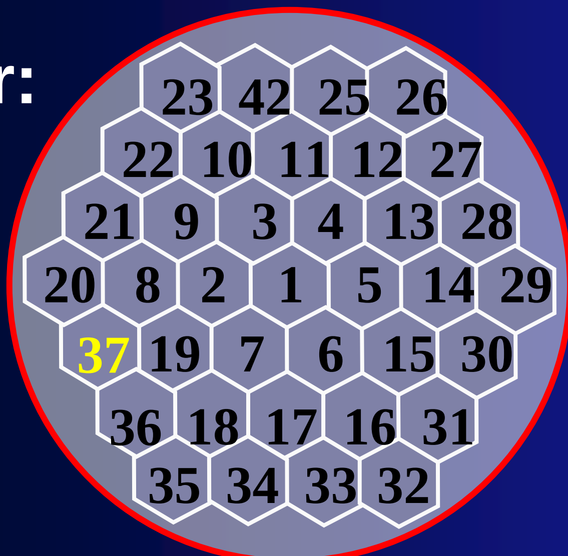
Note that: Membrane is very delicate!!

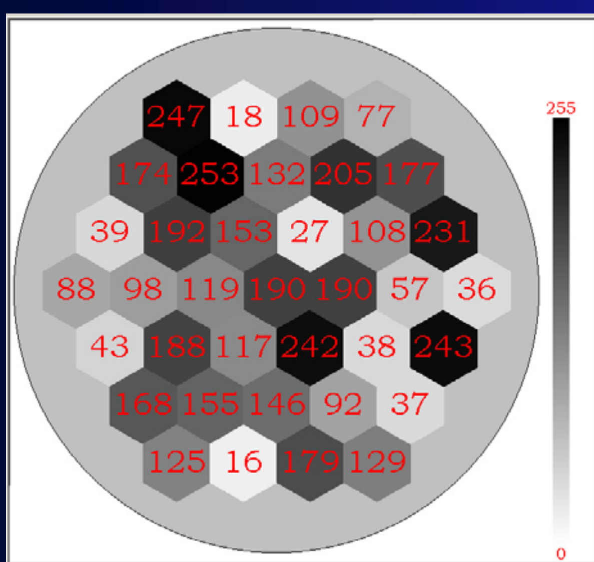
We build N_2-Housing for DM.

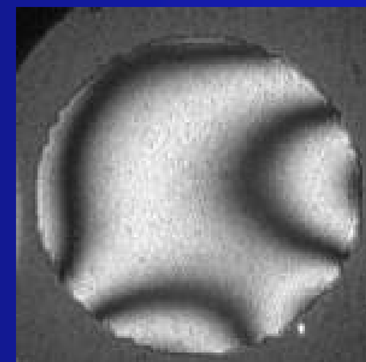
3 - 2 . Spatial profile shaping with DM
3 - 2 - 2 . Deformable Mirror Actuator (ex. 37ch)

Voltage: 0 ~ 255 V

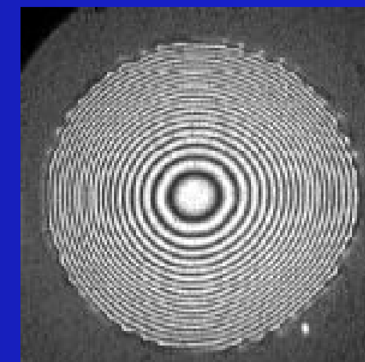
Actuator:



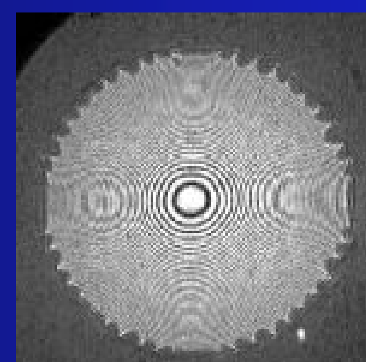




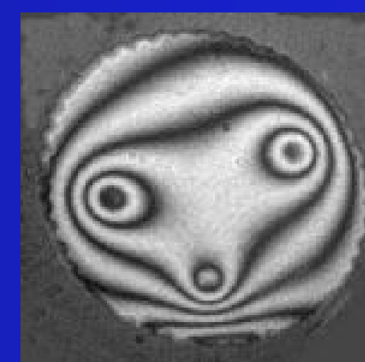
Initial State (All: 0V)



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

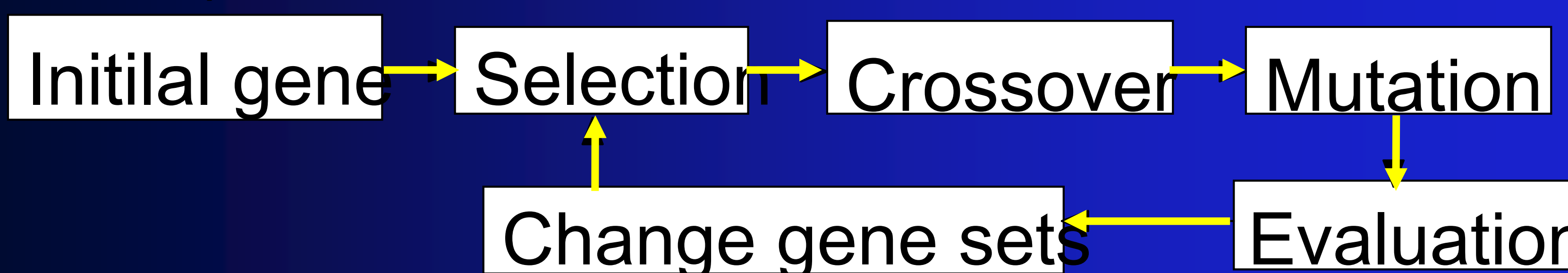
<Basic Process>

1) Coding : Digitize control parameters

gene	1	0	1	1	1	0	0	0

2) Initialization : prepare a sets of gene

3) Basic Process



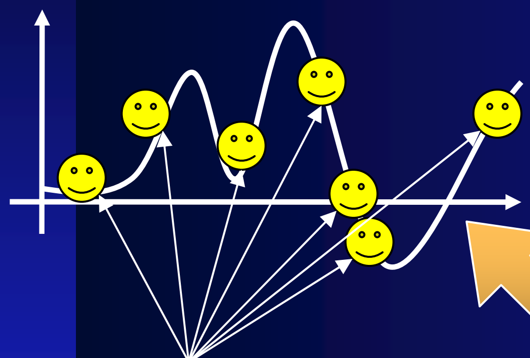
3 - 2. Spatial profile shaping with DM

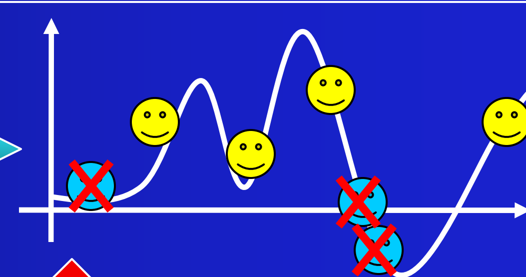
3 - 2 - 4 . Example of Automation of optimization

(Searching maximum point) ～ **Fitting Function** ～

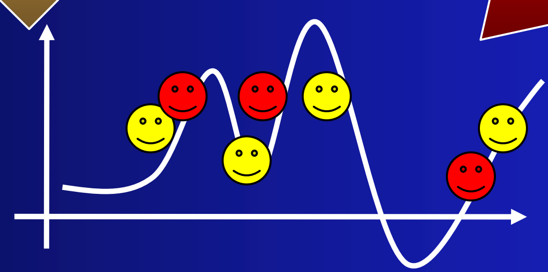
Example :
Search the Maximum Value!!

Searching points near by max. survive.





Iterations



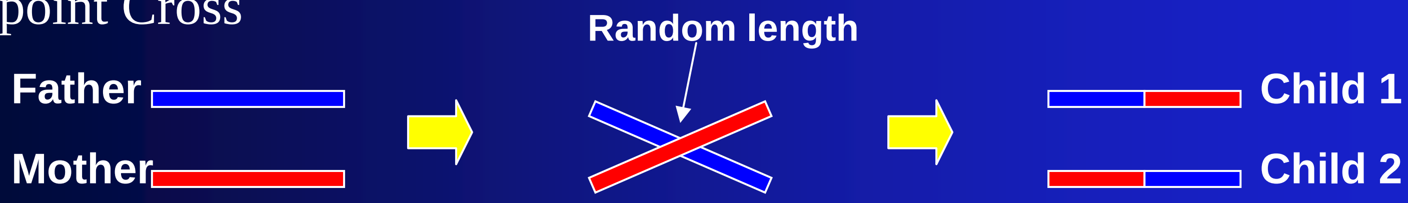
Searching point corresponds to individual life.

The survivors make new generation (Searching point).

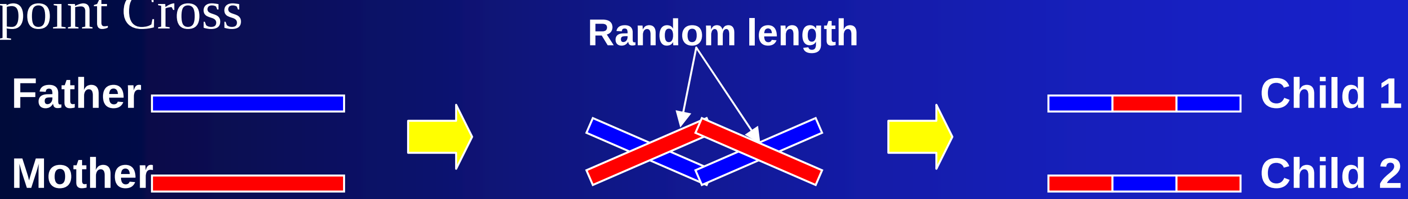
About Children (generation)

How to create children?

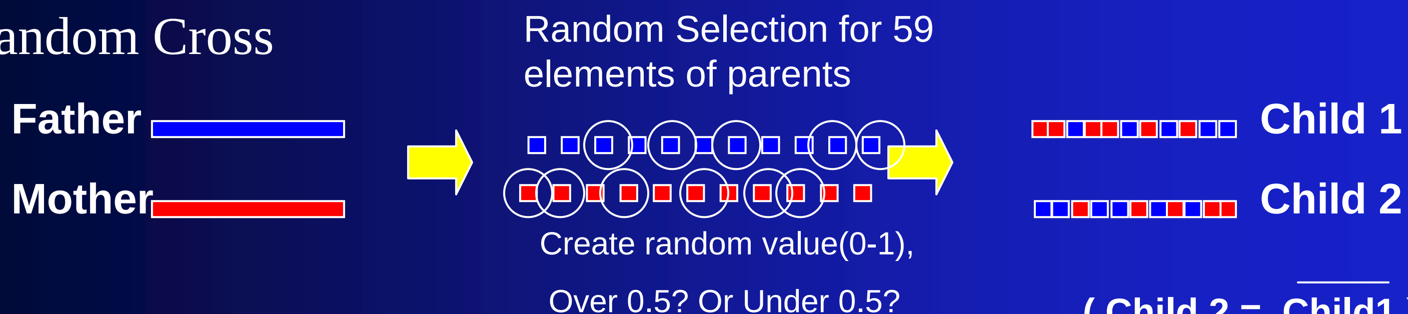
(1) 1 point Cross



(2) 2 point Cross



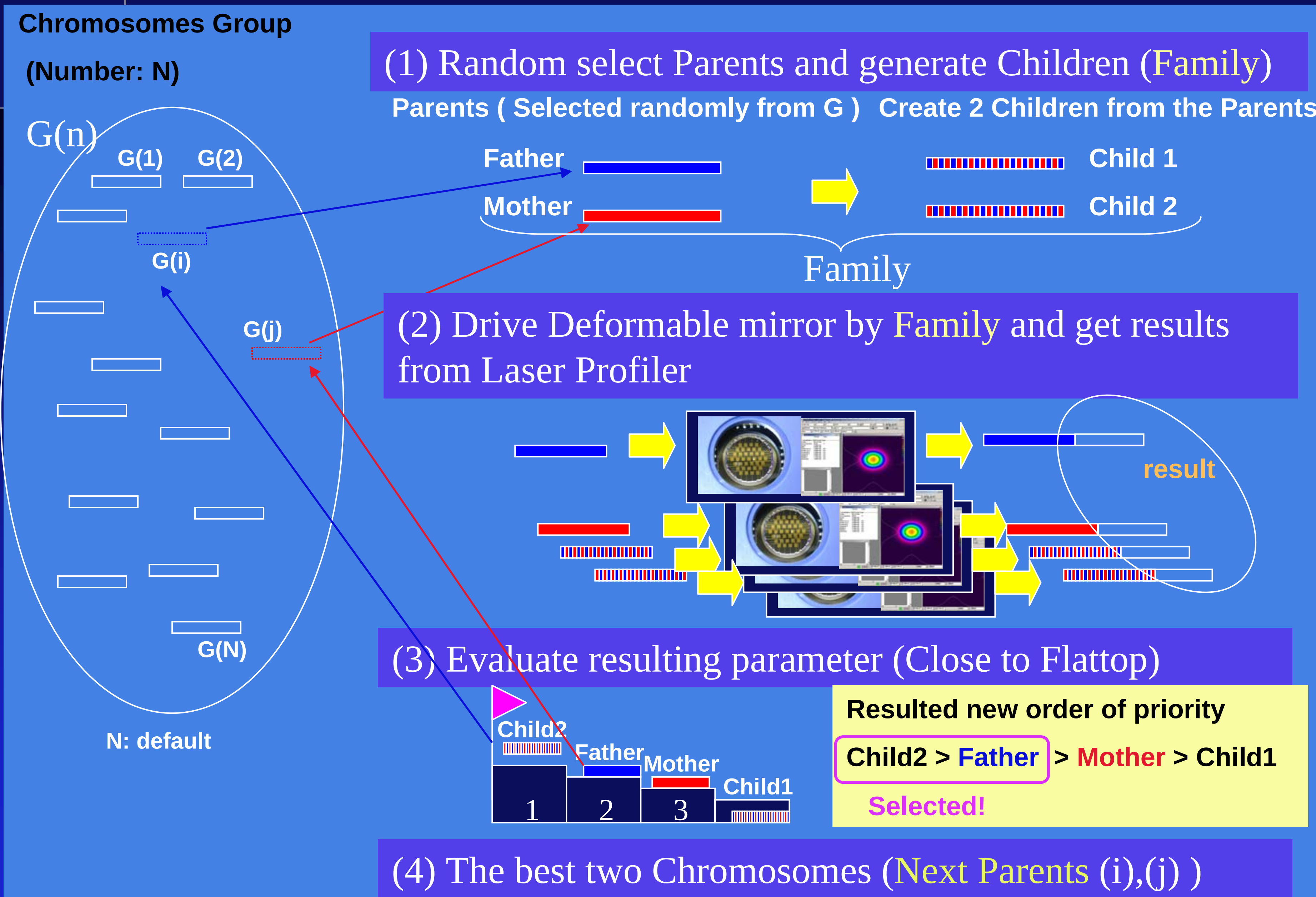
(3) Random Cross



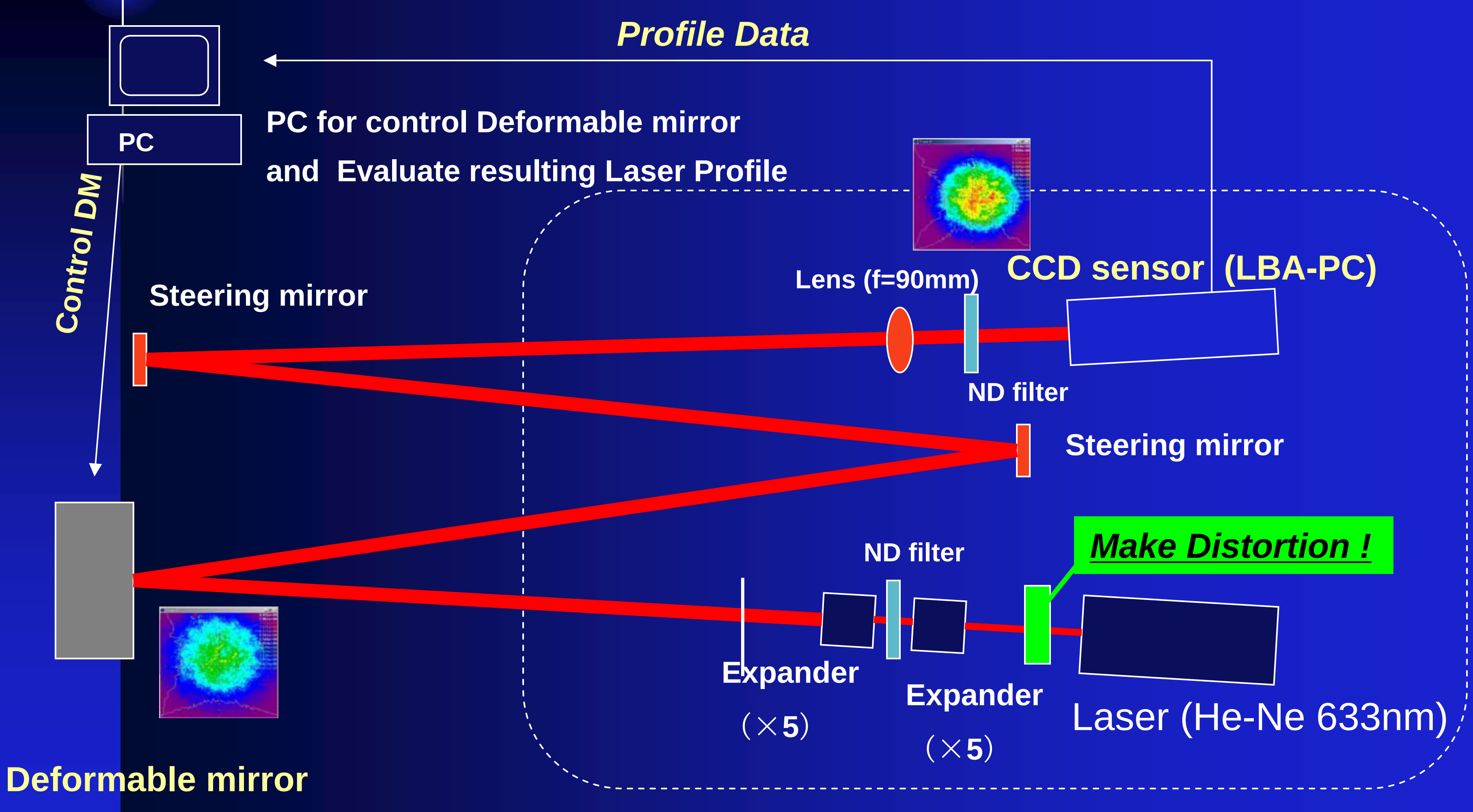
(Child 2 = $\overline{\text{Child1}}$)

Why? Most simple method for programming

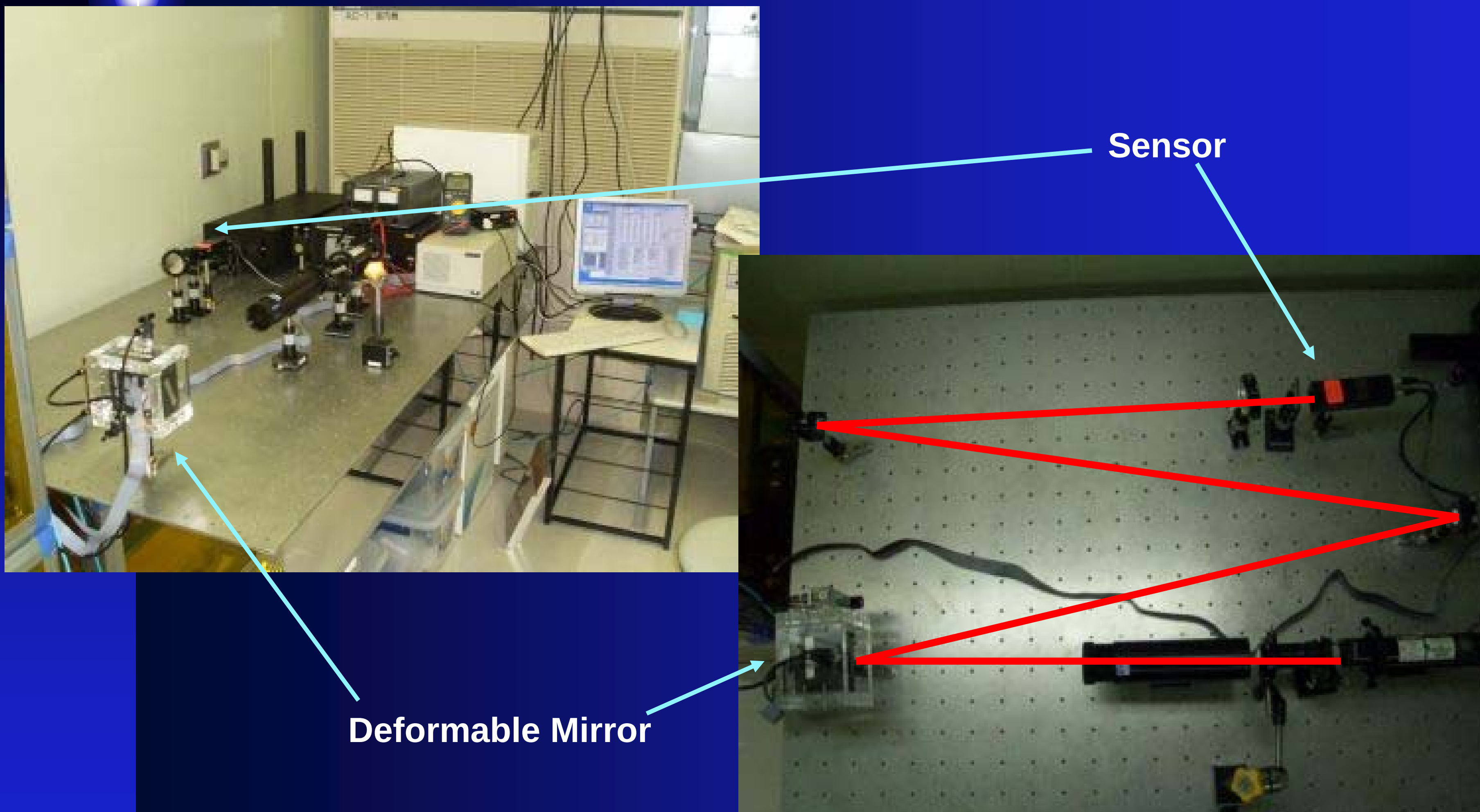
Procedure (1 step)



Closed Control System for experiment



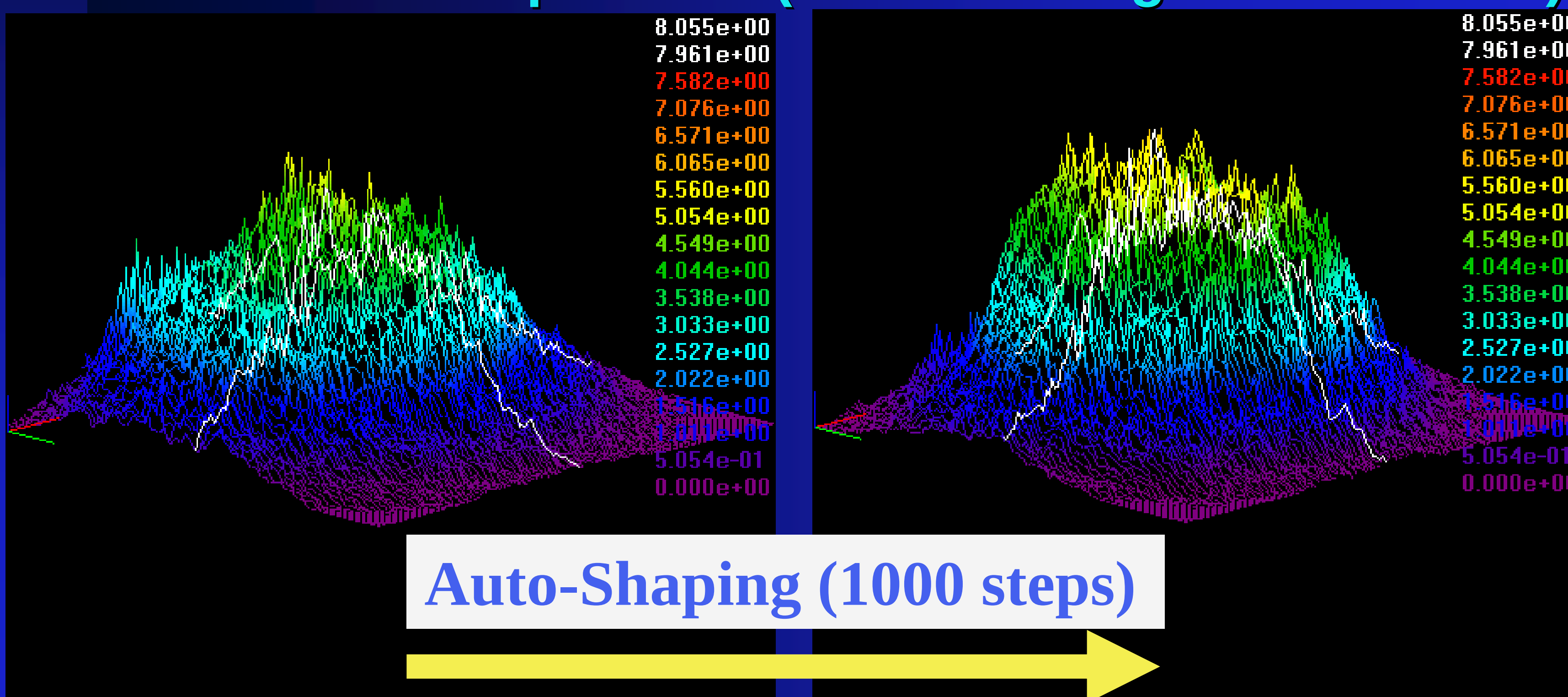
Experiment Setup



3 - 2 . Spatial profile shaping with DM

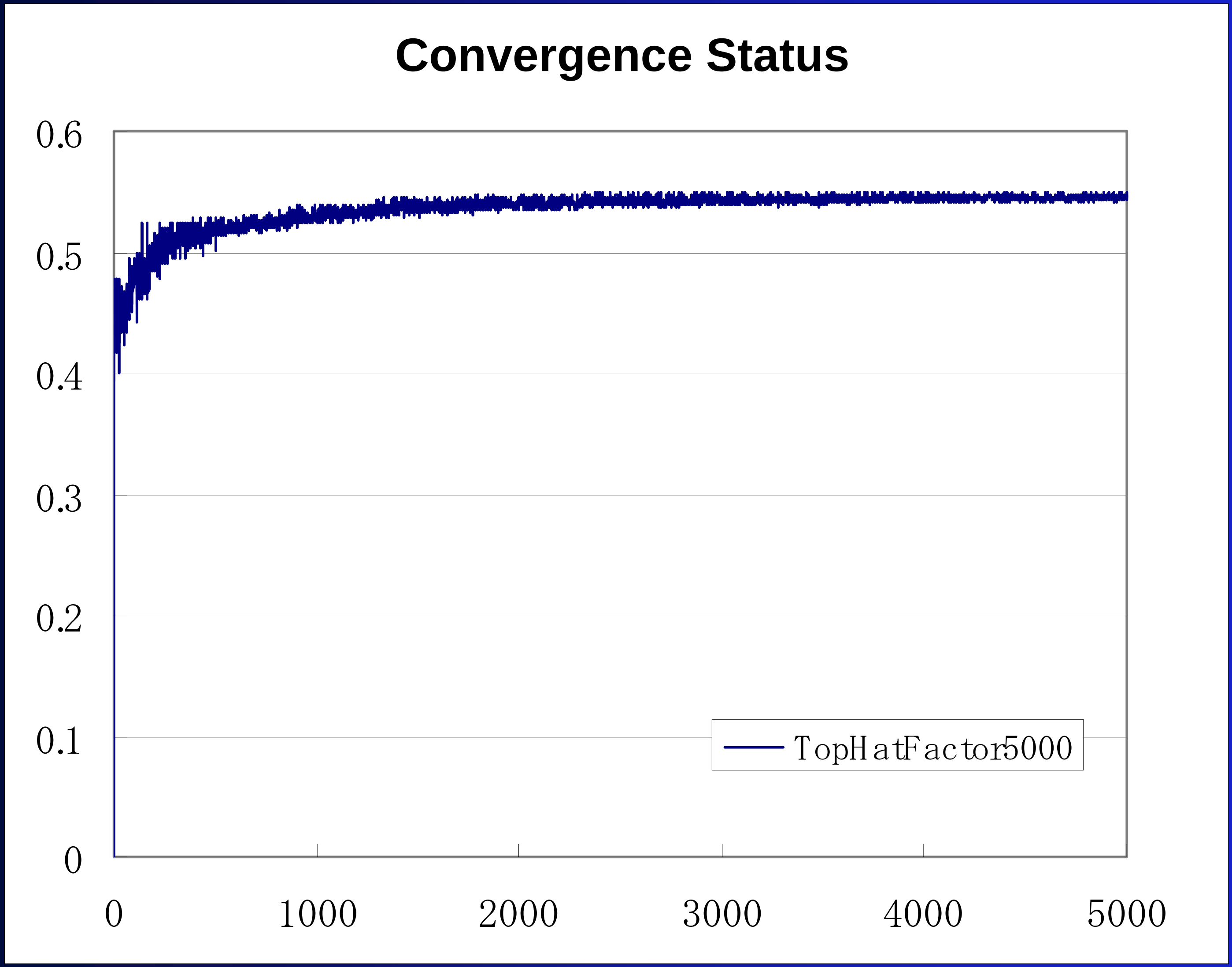
3 - 2 - 5 . Results of the combination DM+GA

- First test for computer-aided **DM** was done with He-Ne
  - ⇨ **Flattop shaping OK!**
- Computer-aided **DM** for UV (THG)
  - ⇨ **No problem (It is installing at THG soon.)**



3 - 2 . Spatial profile shaping with DM

3 - 2 - 5 . Results of the combination DM＋GA



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

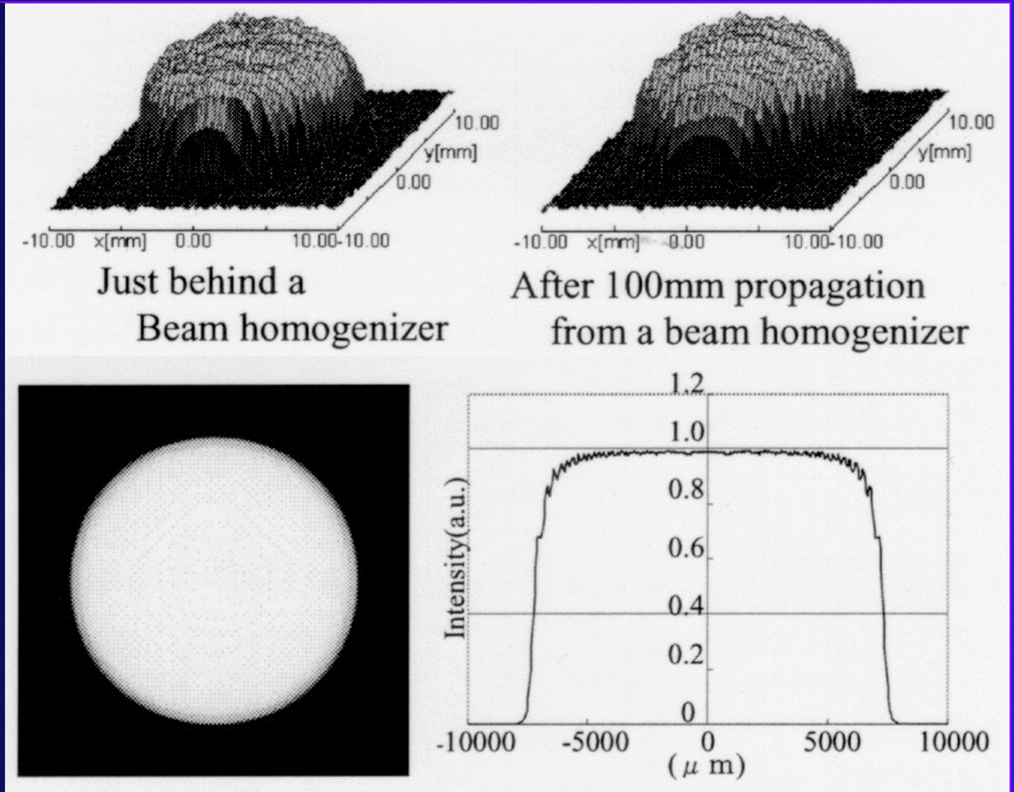


Fig.12 Calculated intensity of the beam homogenized by the designed aspheric homogenizer

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

4．Optimization system of temporal profile

4－1． Spatial Light Modulator (SLM; liquid crysta

~ Computer-controllable optical Phase or Amplitude masks ~

Merit:

- any-pulse shape including square pulse
- possible to control with rapid update (< 0.3 ms)

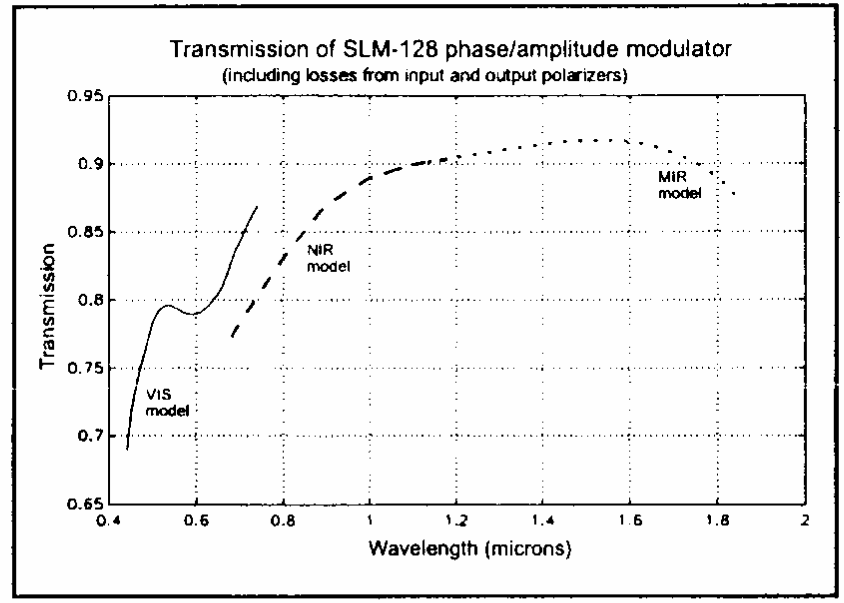


Figure 2. Polarizer transmittance over SLM optics range.

Demerit:

- get distortion of pulse-shape at Amplifier

  ~ install it before Amplifier section.
- not available in UV

Note that: Wave length >425 nm, Pulse energy <10 mJ/cm^2

4 . Optimization system of temporal profile

4 - 2 . Other kinds of SLM

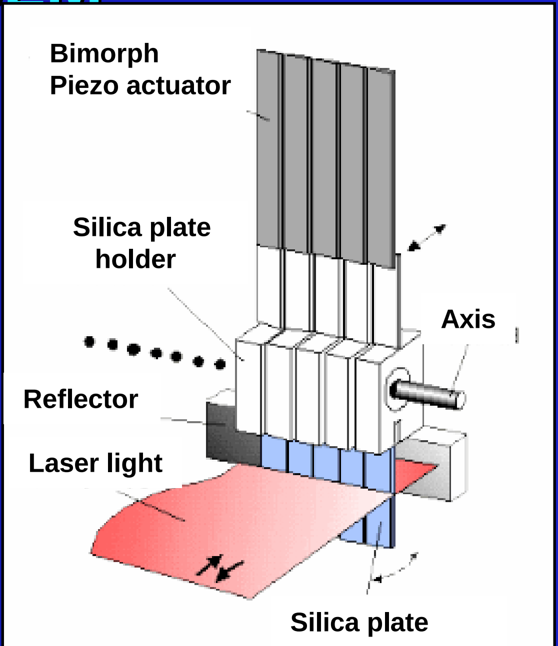
4 - 2 - 1 . DAZZLER (Acousto-optics)

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

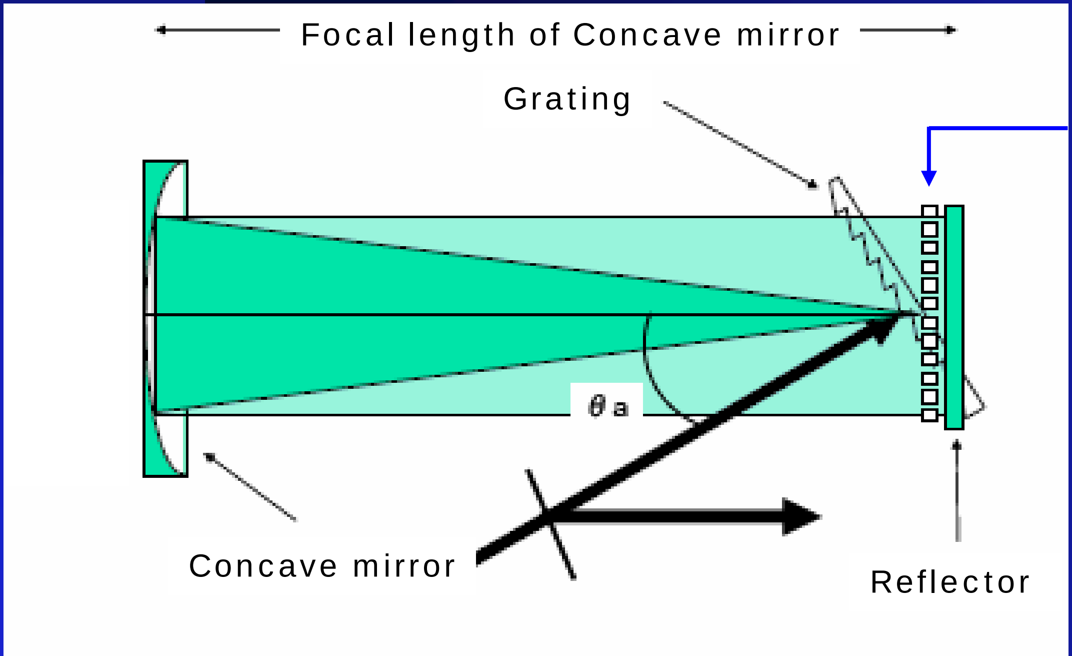
Short laser pulse

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

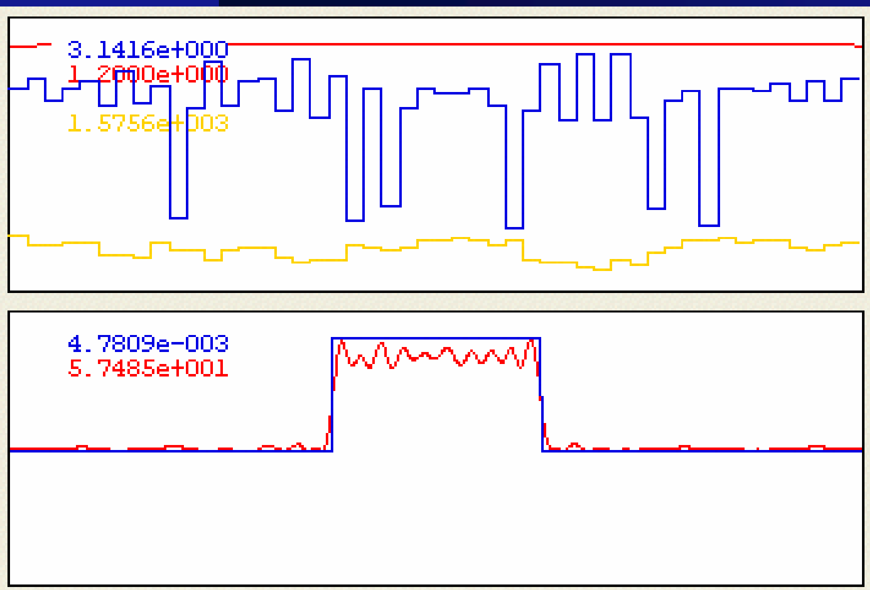
4. Optimization system of temporal profile

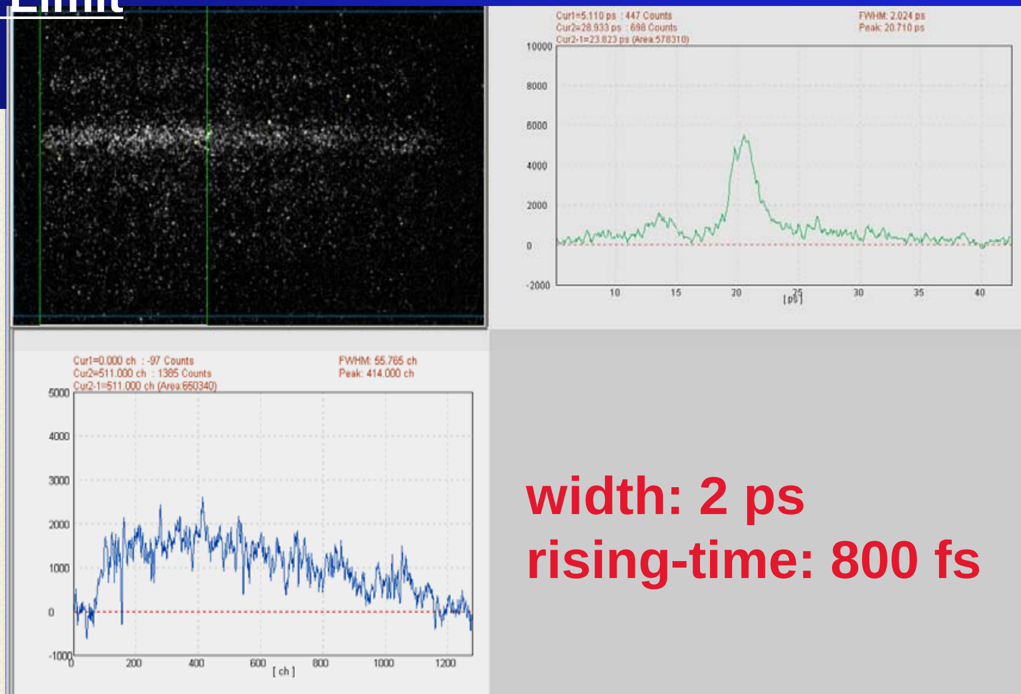
4 - 3 . Results of Pulse Shaping with SLM

- First test for computer-aided **SLM** was done in IR
  - ⇨ **Rectangular Pulse (width range: 2-12 ps)**
  - **(rising-time: 800fs)**
- Computer-aided **SLM** in UV
  - ⇨ **Size will be bigger (~5 times)**

Incident Pulse: Fourrier Transform Limit

Calculate Phase Spectra!





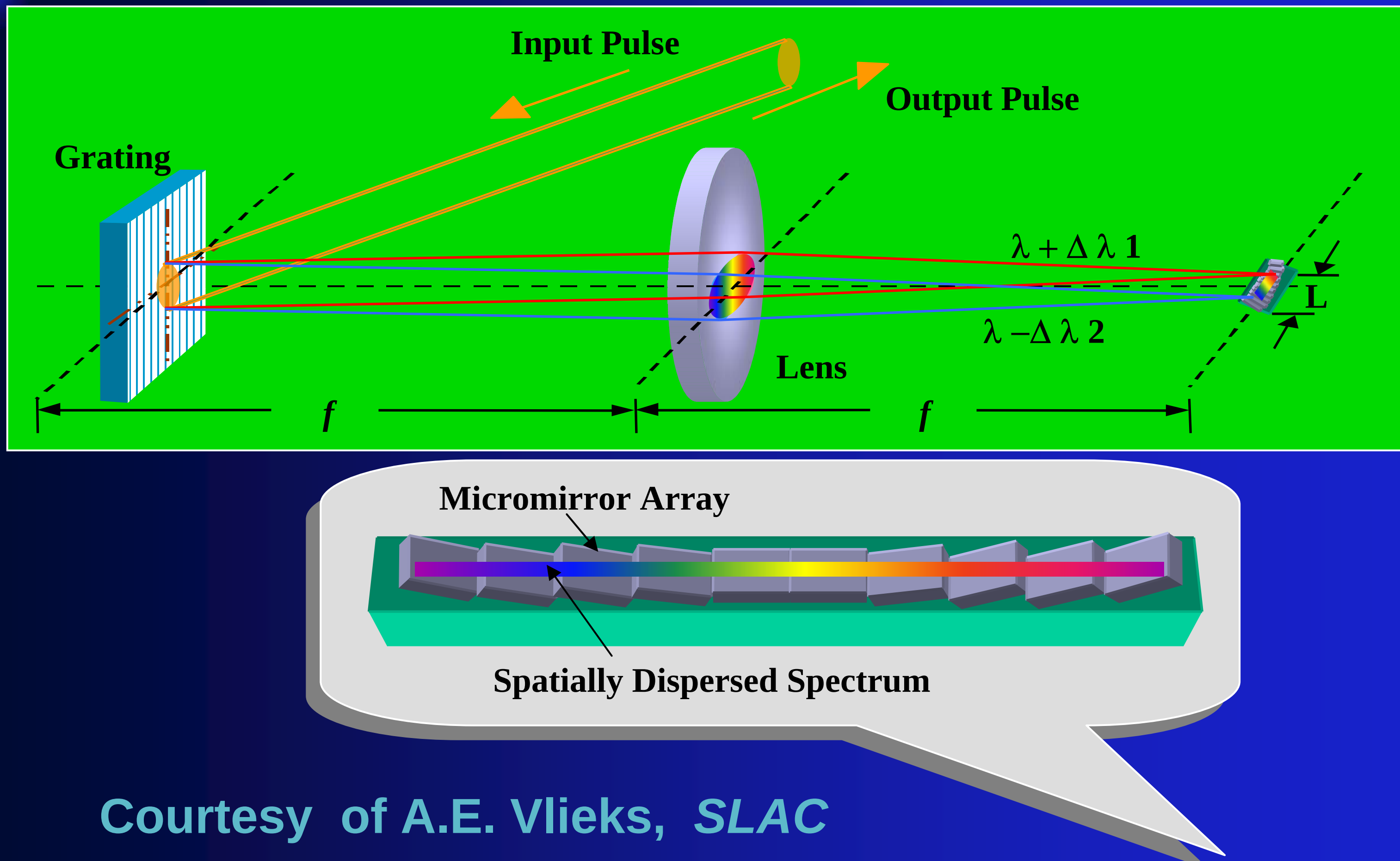
width: 2 ps

rising-time: 800 fs

4 . Optimization system of temporal profile

4 - 4 . Micromirror Array (MMA)

~ Computer-controllable, Possible in UV ~



Courtesy of A.E. Vlieks, *SLAC*

Tilt and vertical displacement enable piecewise linear spatial phase modulation while retaining capability to produce discontinuities for pulse shaping applications. Like a spatial light modulator based pulse shaper, there is no net spatial beam steering.

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 π mm mrad. (Microlens Array)

~ Before installation of Homogenizer, 6.0 π mm mrad. ~

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

~ However, it takes 1 hour to optimize. + DB is necessary. ~

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 < SILACA ~ MMA

perfect Rectenglar Pulse : DAZZLER > SILICA

Size (10cm < 2~5 m) : DAZZLER < SILACA ~ MMA

Cost ($\$10^{3\sim4}$ < $\$10^{4\sim5}$) : SILACA ~ DAZZLER < MMA

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

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

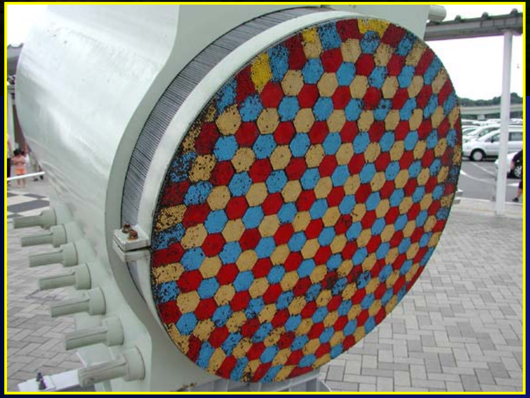
~ It is possible to shape UV-pulse, however size is larger. ~

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

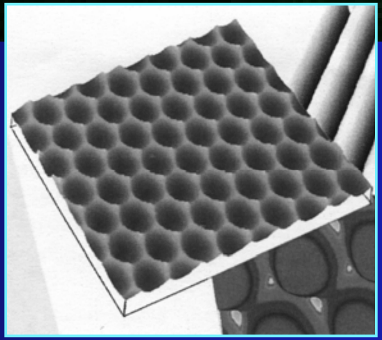
G. In our future plan, compensating any kind of distortion with SLM (Temporal) & e-bunch monitor

Both profiles shaping with Fiber Bundle

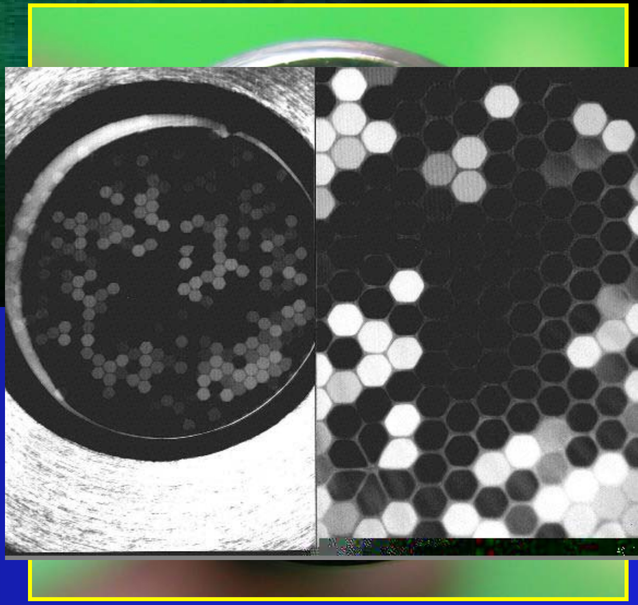
~ FB can 3D-shape the UV-pulse & make easy to transport ~



Cable Strand



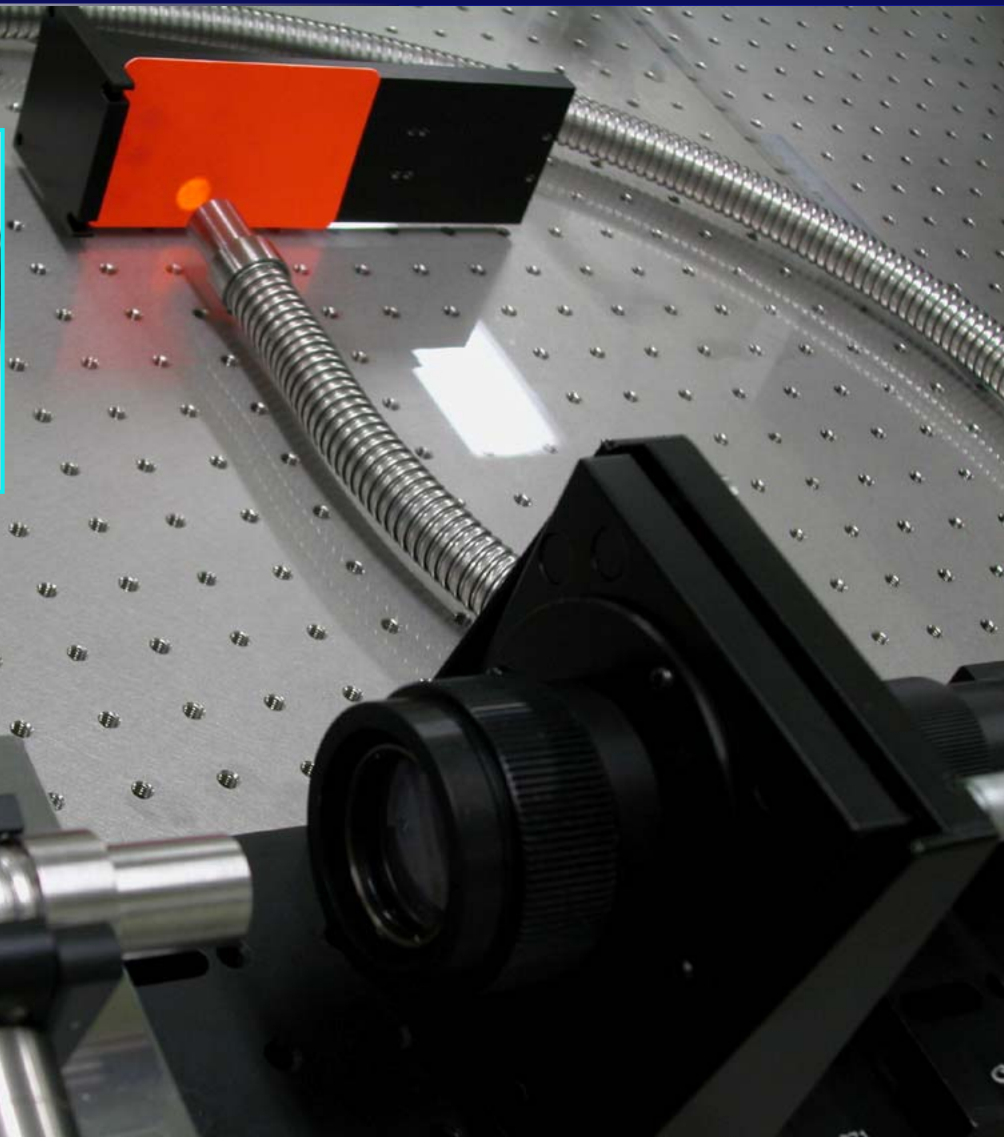
Microlens Array

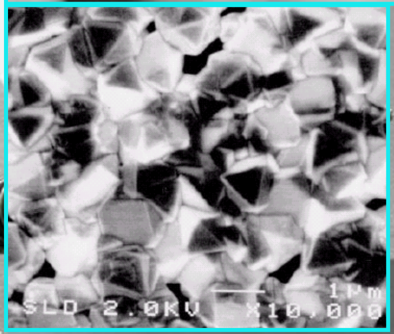


Silica Fiber Bundle

Both profiles shaping with Fiber Bandle

~ Transparent Cathode with Fiber Bundle ~





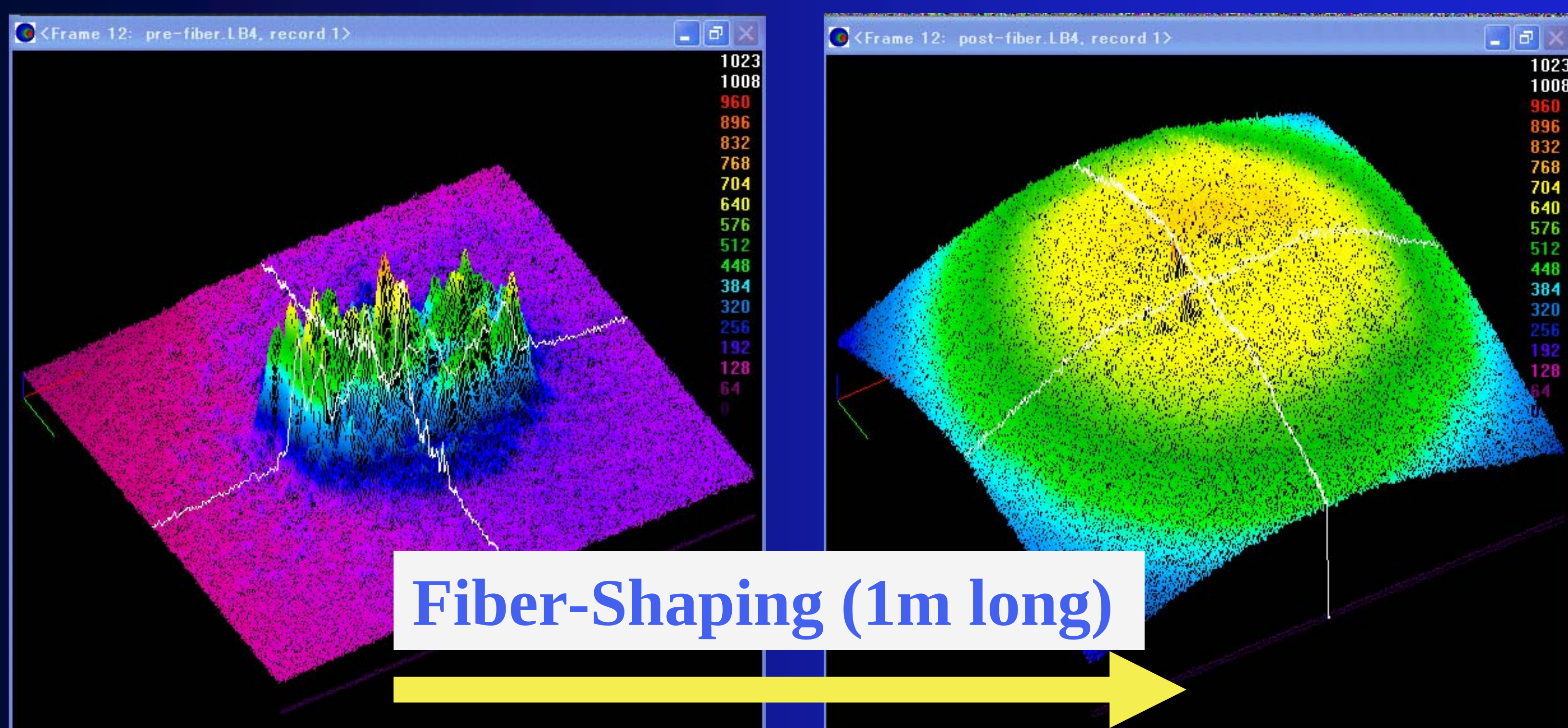
Fiber Bundle:

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

Both profiles shaping with Fiber Bandle

1 . Results of spatial profiles with shaping

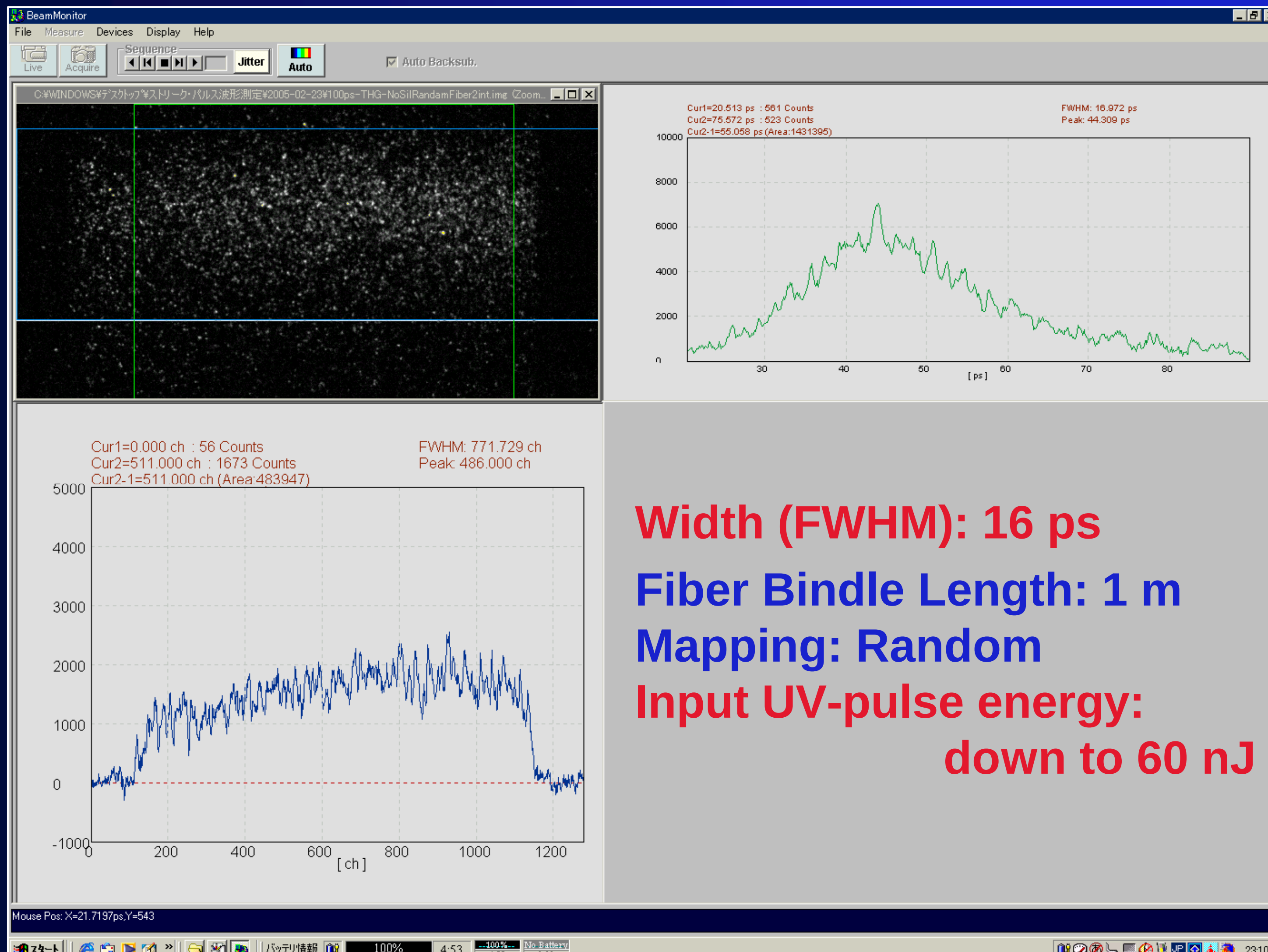
- Spatially homogenizing is very strong with FB
  - ⇨ **Any kind of bad profile can be corrected!**
- Pulse shaping & stretching with FB is **pulse-stacking**
  - ⇨ **Depend on the length and mapping of FB**



Both profiles shaping with Fiber Bandle

2 . Results of temporal profiles with shaping

~ Pulse shaping result due to mainly Pulse Staking effect ~



Tracking Code

Purpose for developing the 3D code

To investigate:

- **asymmetrical effects**, such as the spatial and temporal asymmetrical beam shapes
- **oblique incidence of a laser**
- asymmetrical RF fields

Characteristic of the code

- **Fully 3D**, including:
  - **space charge effect**
  - **image charge effect** of the cathode
- **A charged particle** is treated as **a macro particle**, which is a cluster of electrons
- **Electromagnetic fields** are calculated by the code **MAFIA**

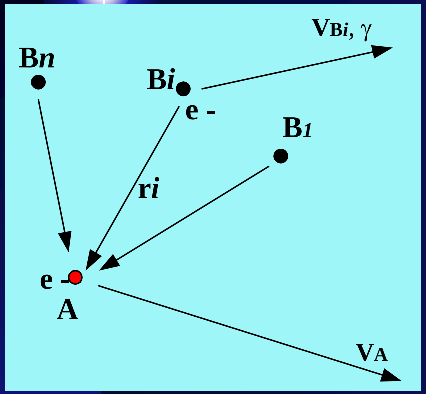
Difficulty of the code

Many particles for precise calculation

→ much elapsed time

Scheme of the code

A) Force calculation between macro particles (ex. 10,000 electrons)



$$\mathbf{E}_A = \frac{1}{4\pi\varepsilon_0}\sum_{i=1}^{n}\frac{-e\mathbf{r}_i}{\gamma_i^2\left[\left|\mathbf{r}_i\right|^2 - \frac{\left|\mathbf{v}_{\mathbf{B}i}\times\mathbf{r}_i\right|^2}{c^2}\right]^{3/2}}$$

$$\mathbf{B}_A = -\frac{e}{4\pi\varepsilon_0 c^2}\sum_{i=1}^{n}\frac{\mathbf{v}_{\mathbf{B}i}\times\mathbf{r}_i}{\gamma_i^2\left[\left|\mathbf{r}_i\right|^2 - \frac{\left|\mathbf{v}_{\mathbf{B}i}\times\mathbf{r}_i\right|^2}{c^2}\right]^{3/2}}$$

$$\frac{d\mathbf{v}}{dt} = -\frac{e}{\gamma m_0}\left(\mathbf{v}\times\mathbf{B} + \mathbf{E} - \frac{(\mathbf{v}\cdot\mathbf{E})}{c^2}\mathbf{v}\right)$$

A: tracking particle

B*i*,(*i*=1,n): source particles for space charge

$$\mathbf{F}_A = -e(\mathbf{E}_A + \mathbf{v}_A\times\mathbf{B}_A) \rightarrow -e(\mathbf{v}\times\mathbf{B}+\mathbf{E}) = \frac{d\mathbf{P}}{dt} = m_0\frac{d(\gamma\mathbf{v})}{dt}$$

Runge-Kutta method

B) Definition of RF phase

$$E_{cavity} = E_{\max} cos(\omega t - \phi)$$

C) Definition of emittance

$$\varepsilon_x = \gamma\beta\sqrt{< x^2 >< x'^2 > - < x\cdot x' >^2}$$