Development of Photocathode RFgun at SPring-8

Hiromitsu TOMIZAWA

JASRI/SPring-8

1. Introduction

- 1.1 Direction of the Research
- 1.2 History
- 1.3 Characteristics of SPring-8 RF gun

1.1 Direction of the Research

- Lowest Emittance Beam Generation based on
  - 3D Laser Shaping with long-term stability
  - 3D Beam Dynamics Simulation
  - Cavity Technology for Higher RF Field
  - New Cathode Developments
  - High Resolution Emittance Monitor

1.2 History

1996 Study of photocathode RF guns started for the next generation photon source

1999 First beam test
A new laser system ordered

2001 New Ti:Sapphire laser system installed

2002 Emittance 2 πmmmrad with homogenizing
Cartridge type cathode development started

2003 New gun & laser test room constructed and an accelerating structure installed

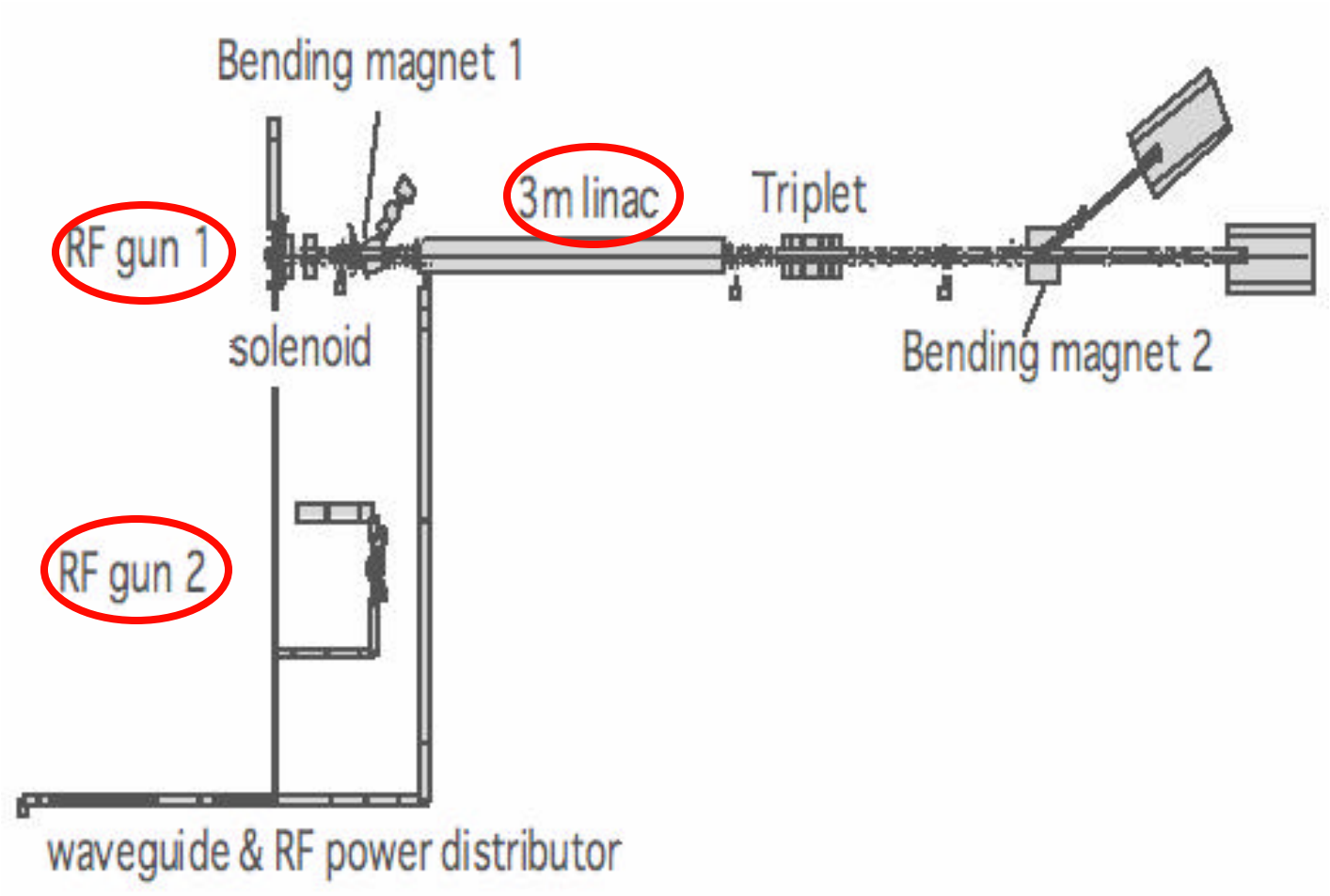
2004 Maximum field of 190 MV/m at cathode
Laser was stabilized with 0.2% for 1 Month

2005 3D-laser shaping system was completed
Emittance 1.7 πmmmrad with Flattop (DM)

1.3 Test Facility

RFgun1 + 3m accelerating structure ------> Low emittance beam production

RFgun2 -----> cathode study, rf breakdown study, surface physics



1.4 Characteristics of SPring-8 RFgun

1. Laser

- THG of Ti:Sa Laser (263 nm, 10Hz, 850 μJ/pulse)
- Energy stability (passive) : 0.7% rms @THG(263 nm)
- Spatial profile control : Homogenizer (or Deformable Mirror)
- Temporal distribution : Stretched with SiO_2 rods (or SLM)
- 3D-Ellipsoidal : Fiber Bundle with Deformable Mirror

2. RF cavity

- S-band (2856MHz), Single-cell pill-box type
- Cathode : cavity wall (RF cavity1)
  cathode plug in a vacuum cartridge (RF cavity2)
- High electric field on cathode : 190 MV/m (RF cavity1)

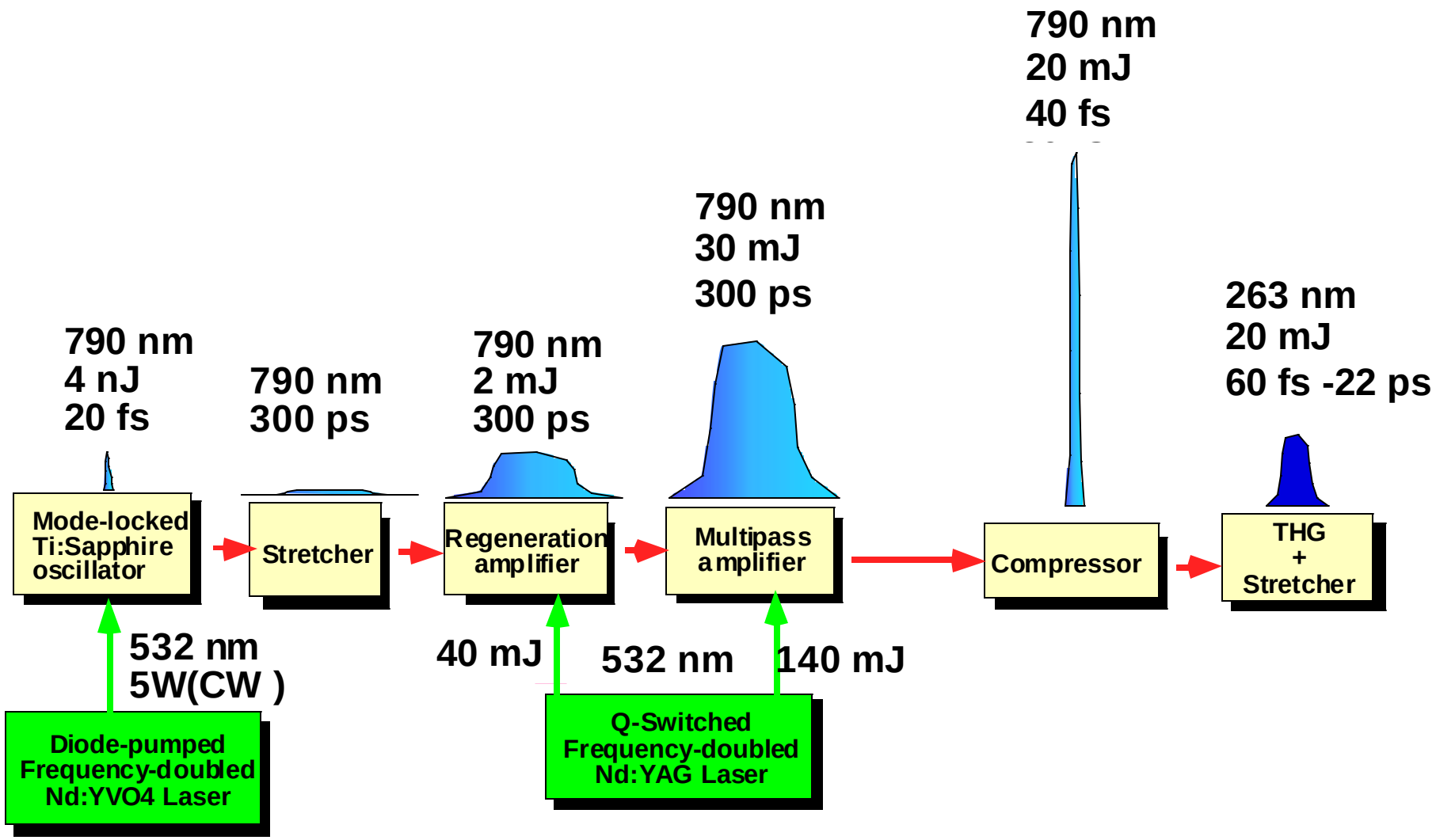
3. Synchronization of Laser & RF

- RF generation(2856 MHz) from laser pulses(89.25 MHz)
- RMS jitter (@low level) < 100 fs

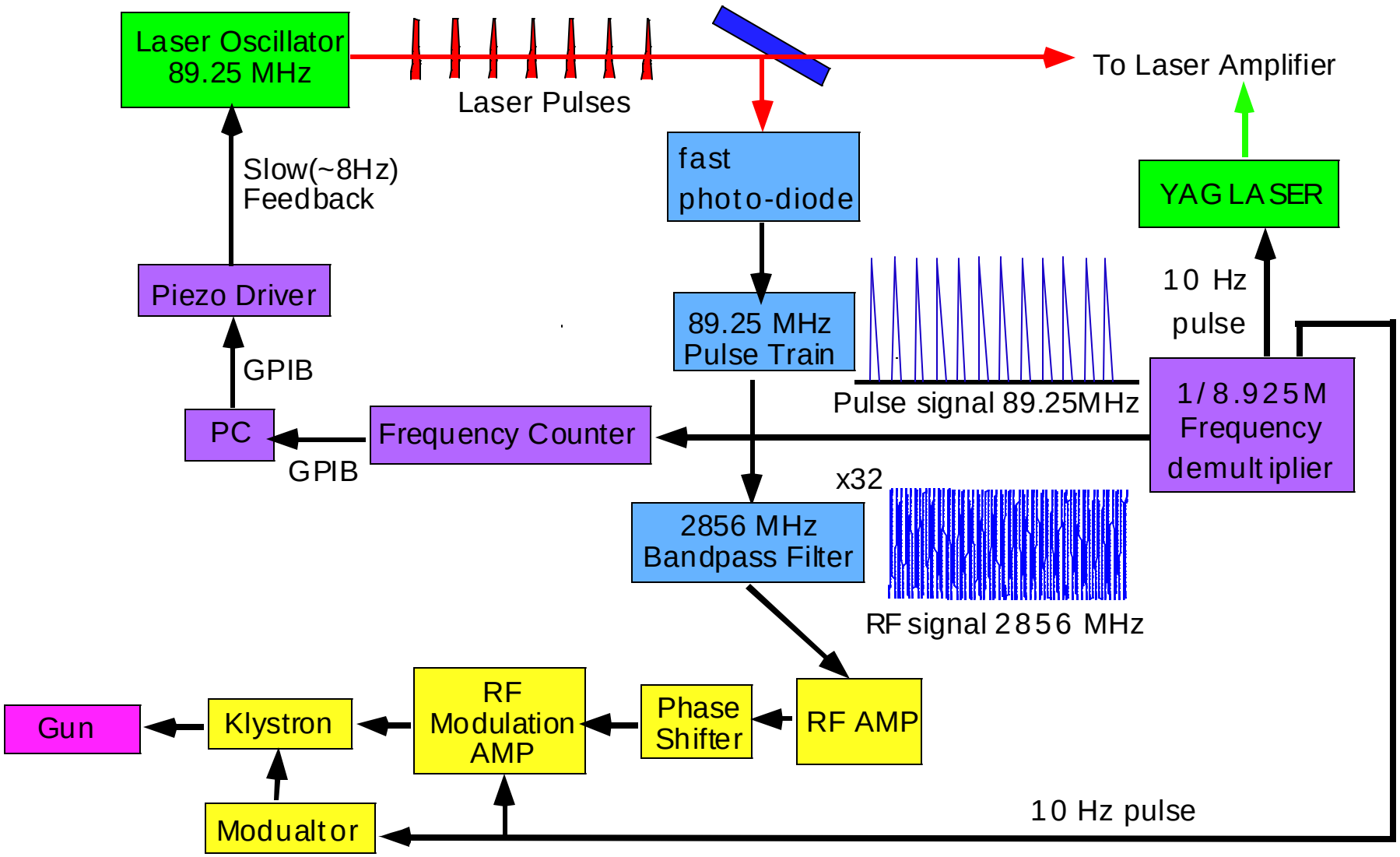
2. Laser

- 2.1 Laser System Configuration
- 2.2 Laser & RF Synchronization
- 2.3 Laser Profile Control
- 2.4 Long-term Stability of Laser

2.1 Laser System Configuration



2.2 Laser & RF Synchronization

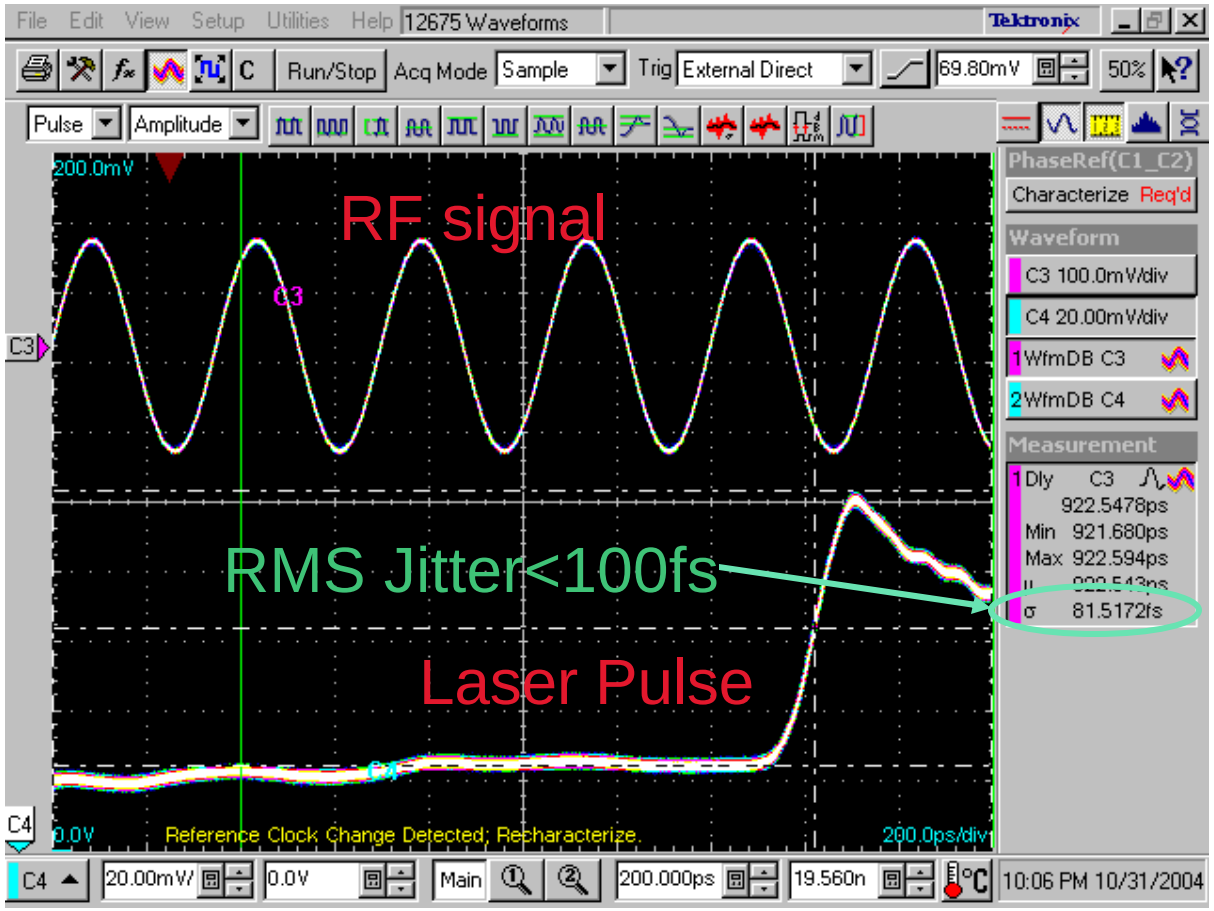


Comparison of synchronization techniques

Laser generation with master RF	RF generation from Laser pulse
using PLL	No PLL
Synchronization is limited by the motion speed of piezo device.	Synchronization is not limited by the motion speed of piezo device.

Combination of both techniques will be planed for further lower jitter .

Short Time Jitter Measurement



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

2-3. Optimization of laser profiles

~ Spatial & Temporal ~

<u>Beam Quality Control by</u>

Spatial Shaping

Microlens Array

Deformable Mirror

Pulse (Temporal) Shaping

SLM (Spatial Light Modulator)

Wave Front Control

Deformable Mirror

3D-laser pulse shaping (ellipsoidal)

Fiber Bundle (Er: Fiber Bundle Laser)

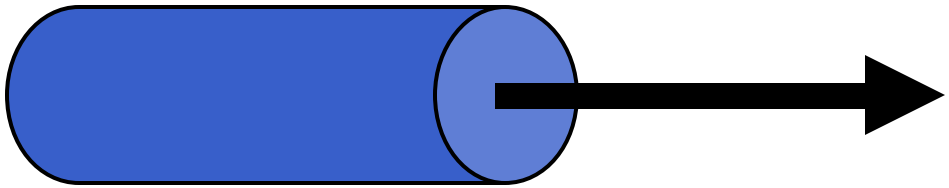
2.3.1 Physical background of ideal laser profile

$$S = \sqrt{S_{SC}^2 + S_{RF}^2 + S_{Th}^2}$$

Space charge effect consists of:

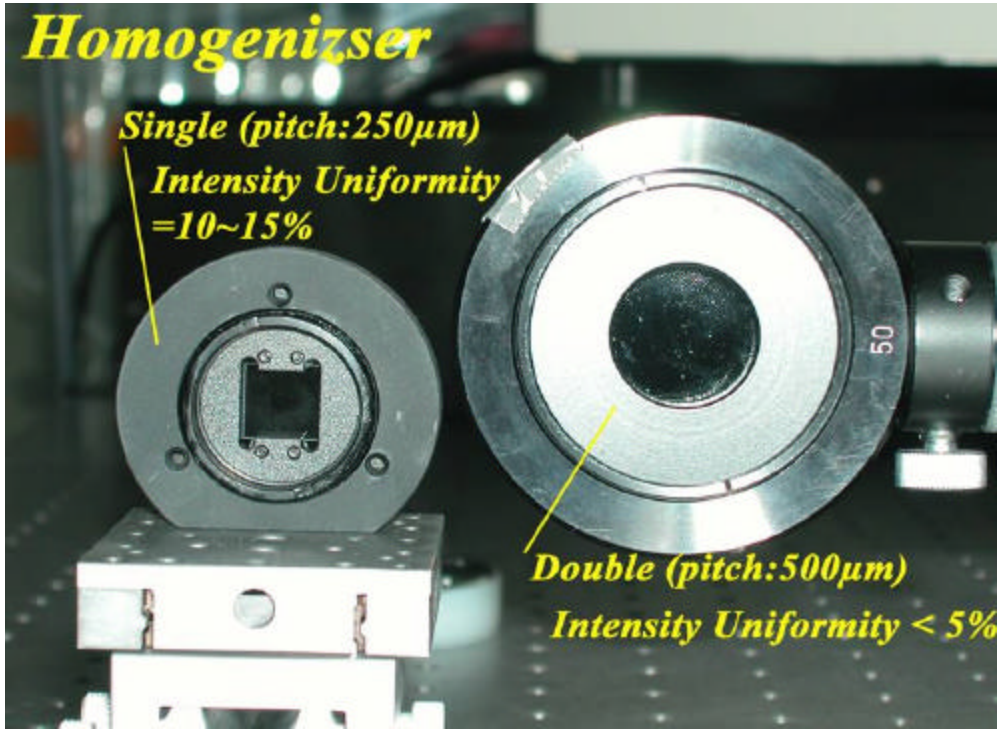
1. **Linear term in radial direction**
   ……possible to compensate with Solenoid Coils

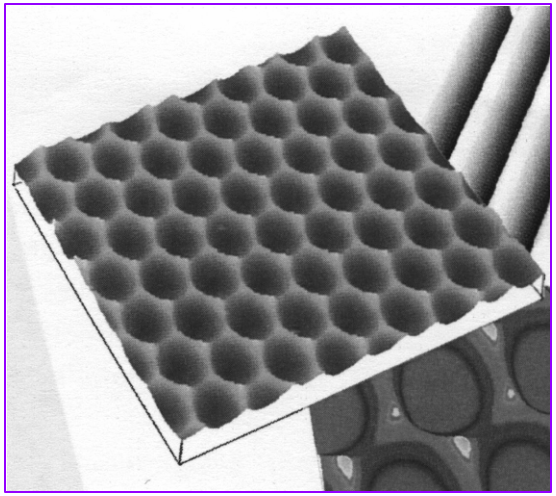
2. **Non-linear term in radial direction**
   ……possible to suppress non-linear effects
   with optimization of ideal Laser Profile

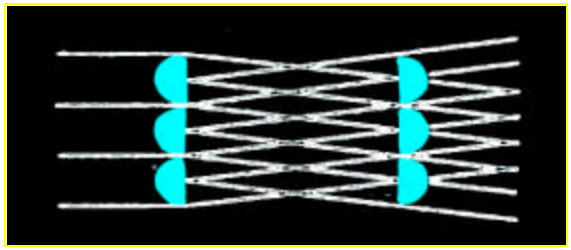


Note that, in real case ideal 3D-shape can be different!

2.3.2 Spatial shaping with microlens array



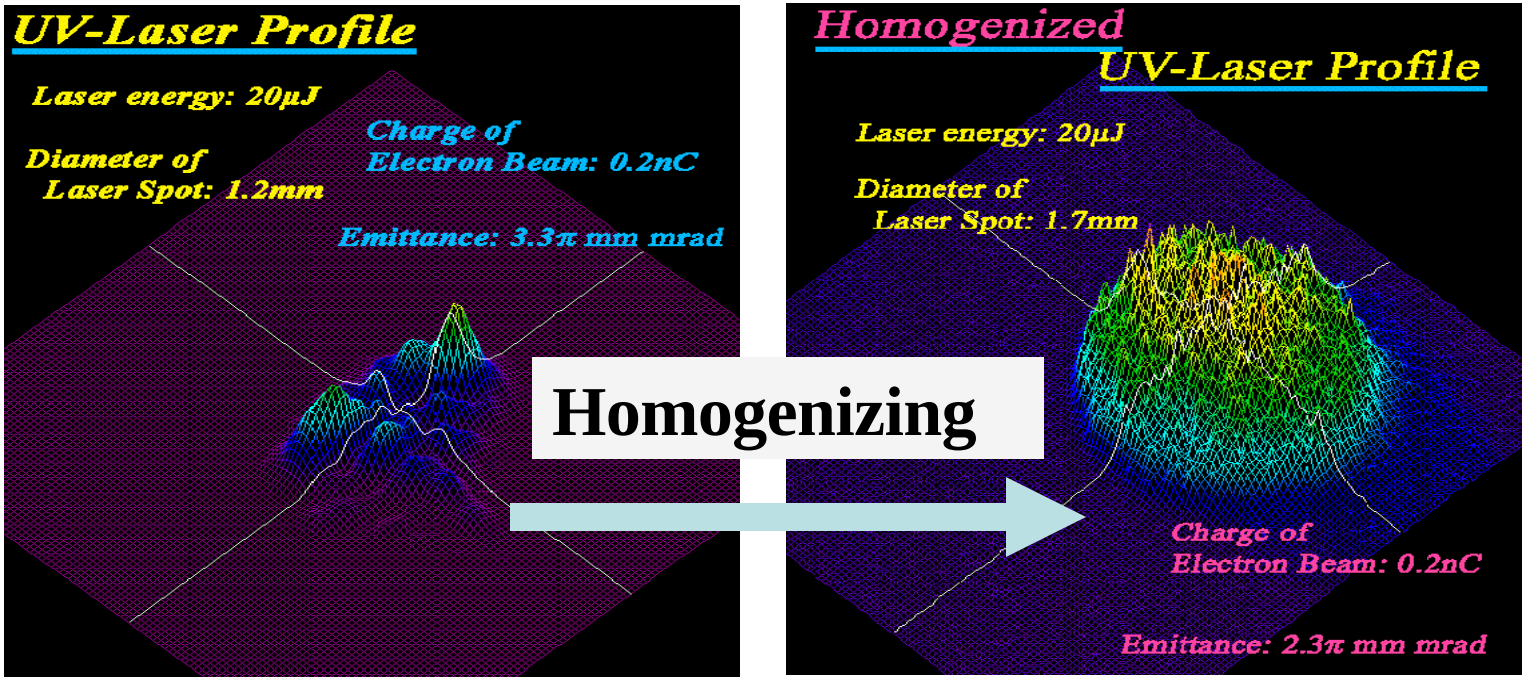




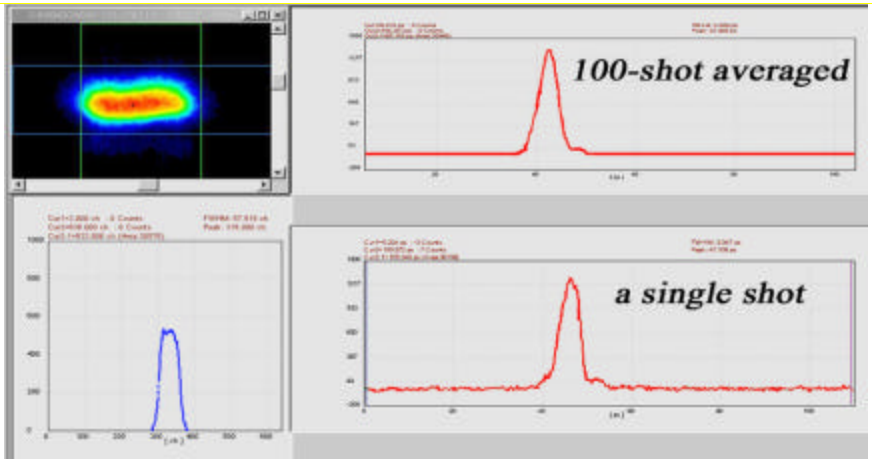
Structure of Microlens Array and the function

2.3.3 Measurement of Laser Pulse Profile

Spatial:



Temporal:



Spot size: 2.0 mm

Pulse width: 5 ps

(45-cm Fused Silica **x 2**)

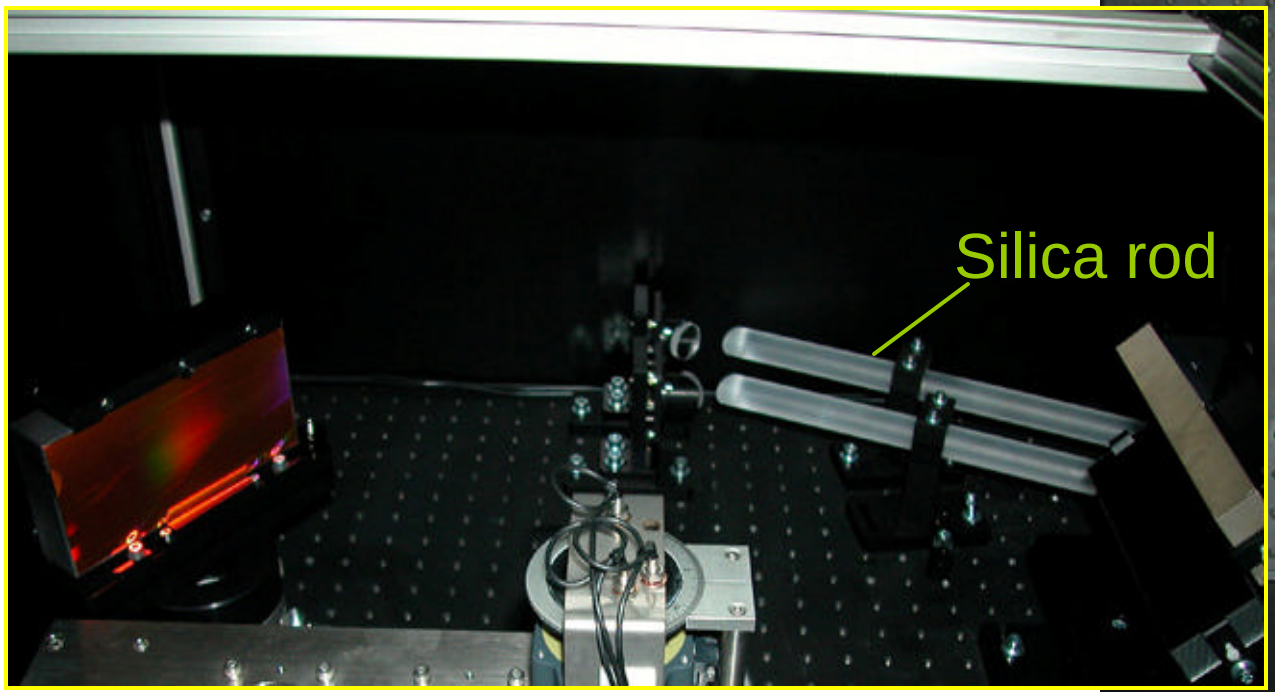
2.3.4 THG Pulse Silica-rod Stretcher

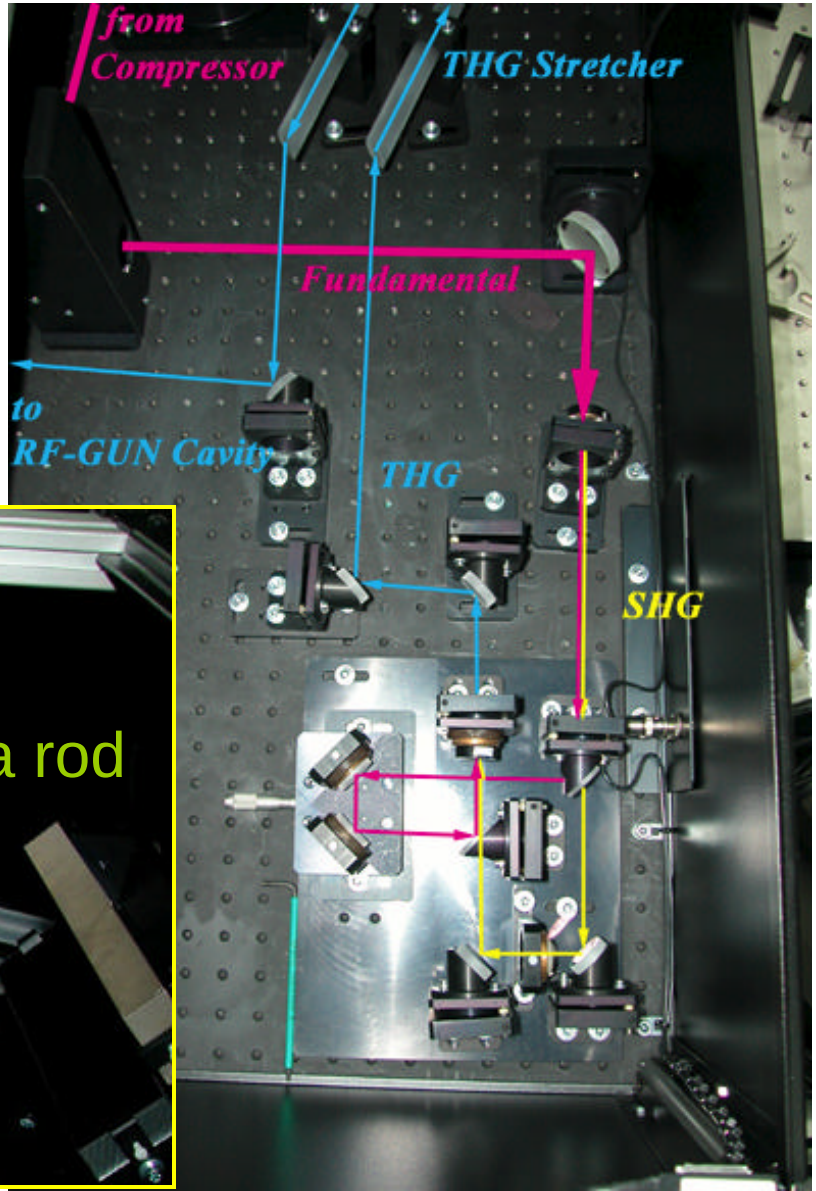
- utilizing the dispersion in Silica -

Possible: Pulse Duration

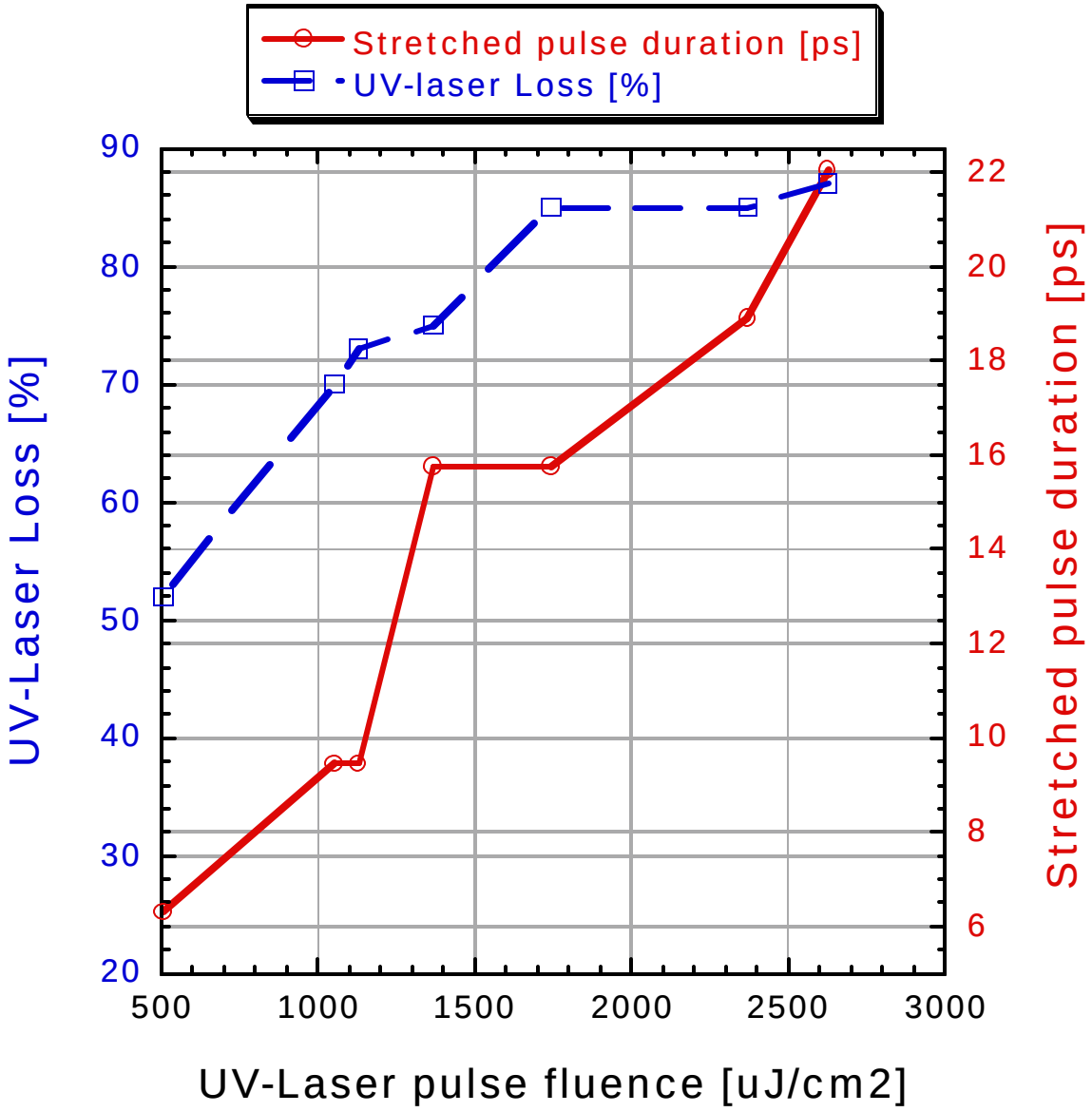
Impossible: Square Pulse

~ 90 % pulse energy will be loss ~



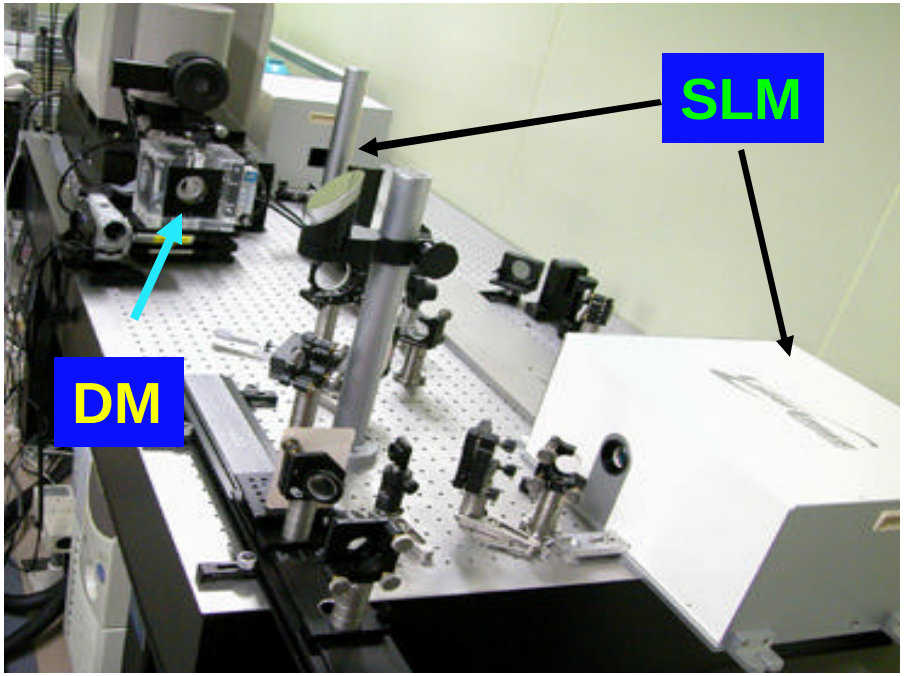


2.3.5 Pulse stretching effect in Silica rods



2.3.6 Automatic laser-beam control system

- Computer-aided **SLM (Spatial Light Modulator)**
  → **Rectangular Pulse shaping (+SA)**
- Computer-aided **DM (Deformable mirror)**
  → **Flattop spatial profile (+GA)**



Automatic Control Optics

- **Spatial shaping (DM)**
- **Pulse shaping (SLM)**
- **Wave front Control (DM)**

Additional function

- **Pointing control (DM)**
- **Pulse energy (SLM)**

2.3.7 Pulse shape control with SLM

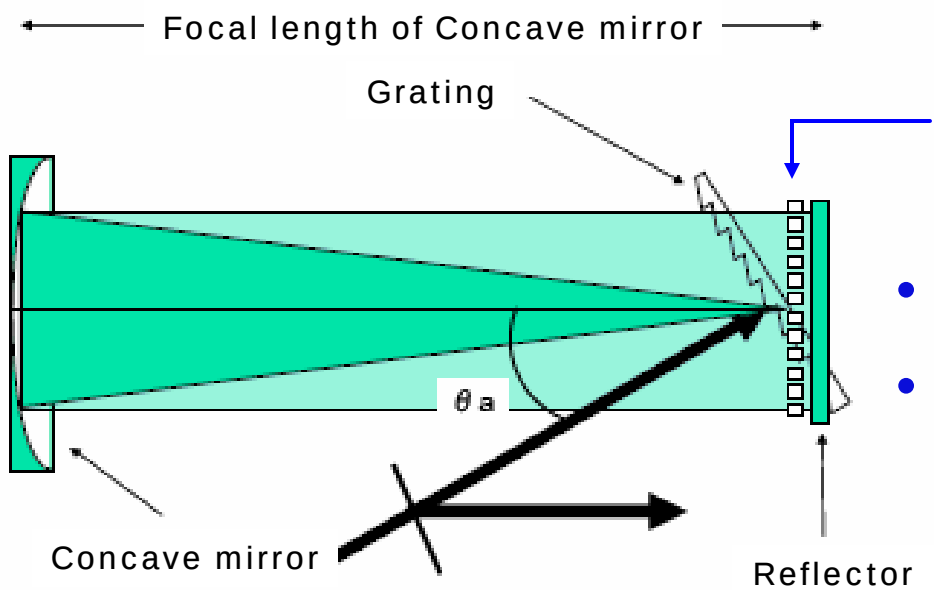
Short laser pulse

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

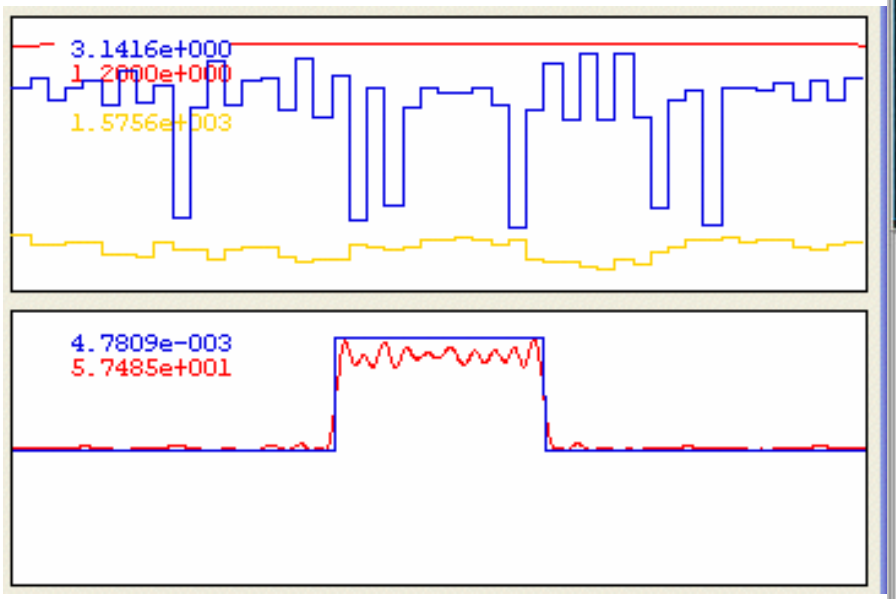
< 100 mJ/cm2

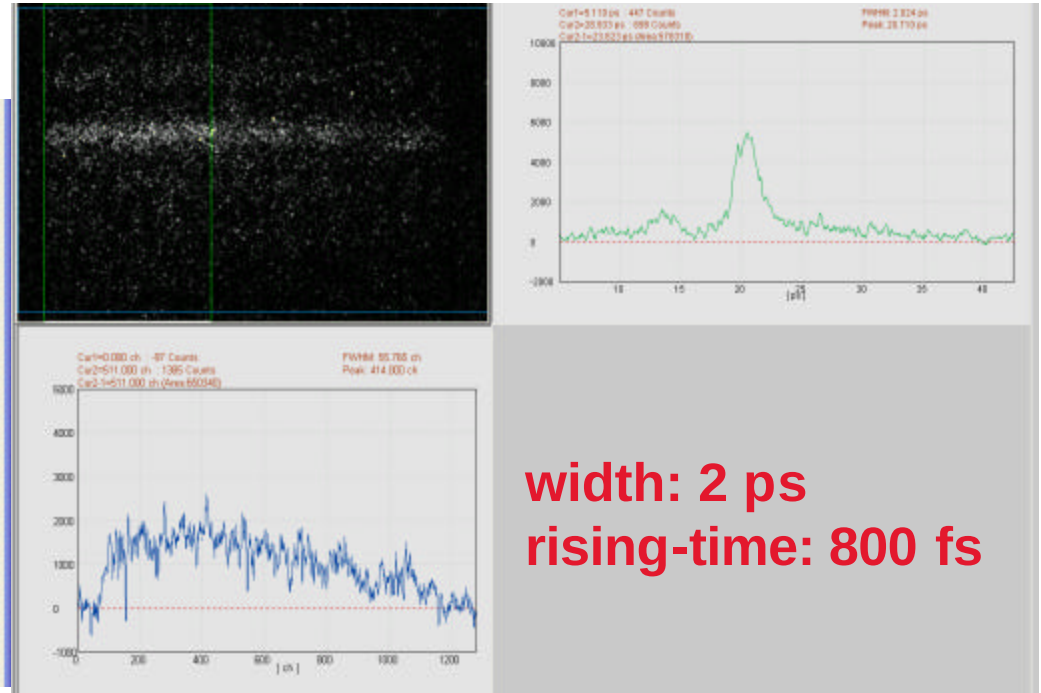
2.3.8 Results of Pulse shaping with SLM

- 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!



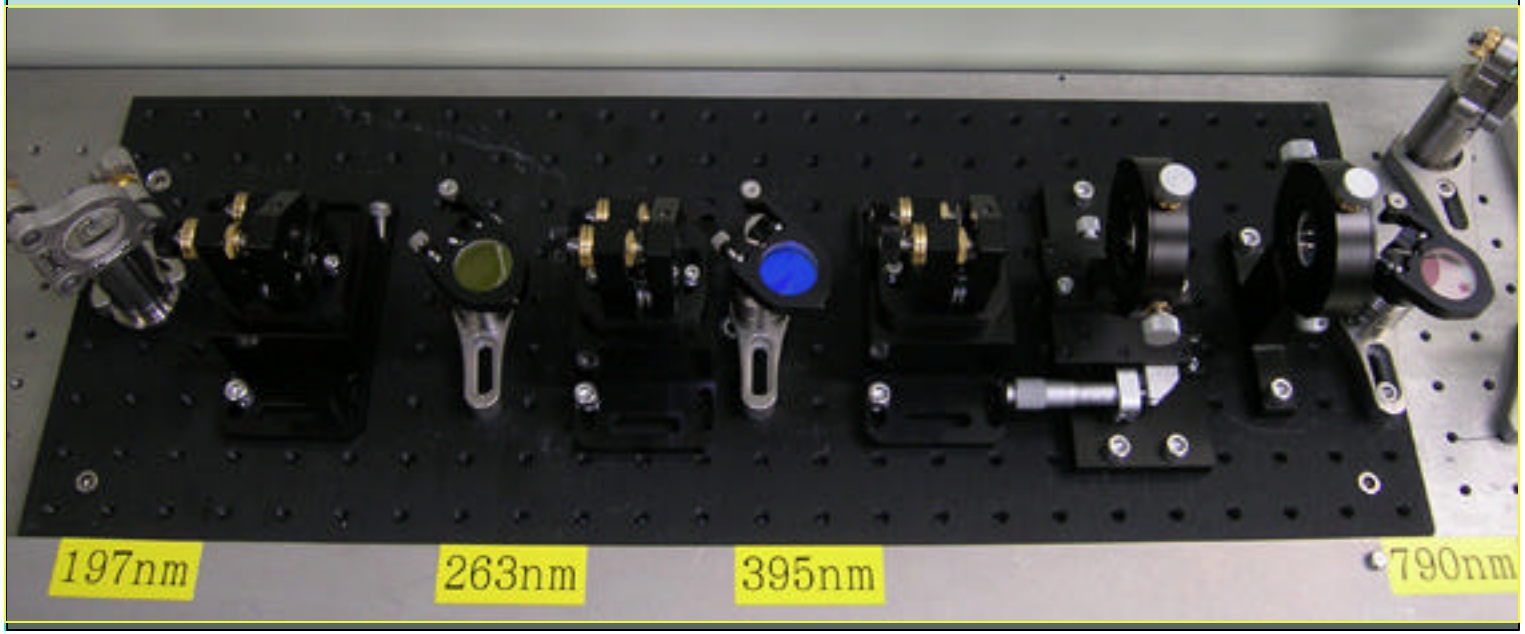


width: 2 ps
rising-time: 800 fs

FHG(197nm), THG(263nm), SHG(395nm)- System

Squared UV- Laser Pulse is generated after shaping with SLM

At present, optical transport is under construction



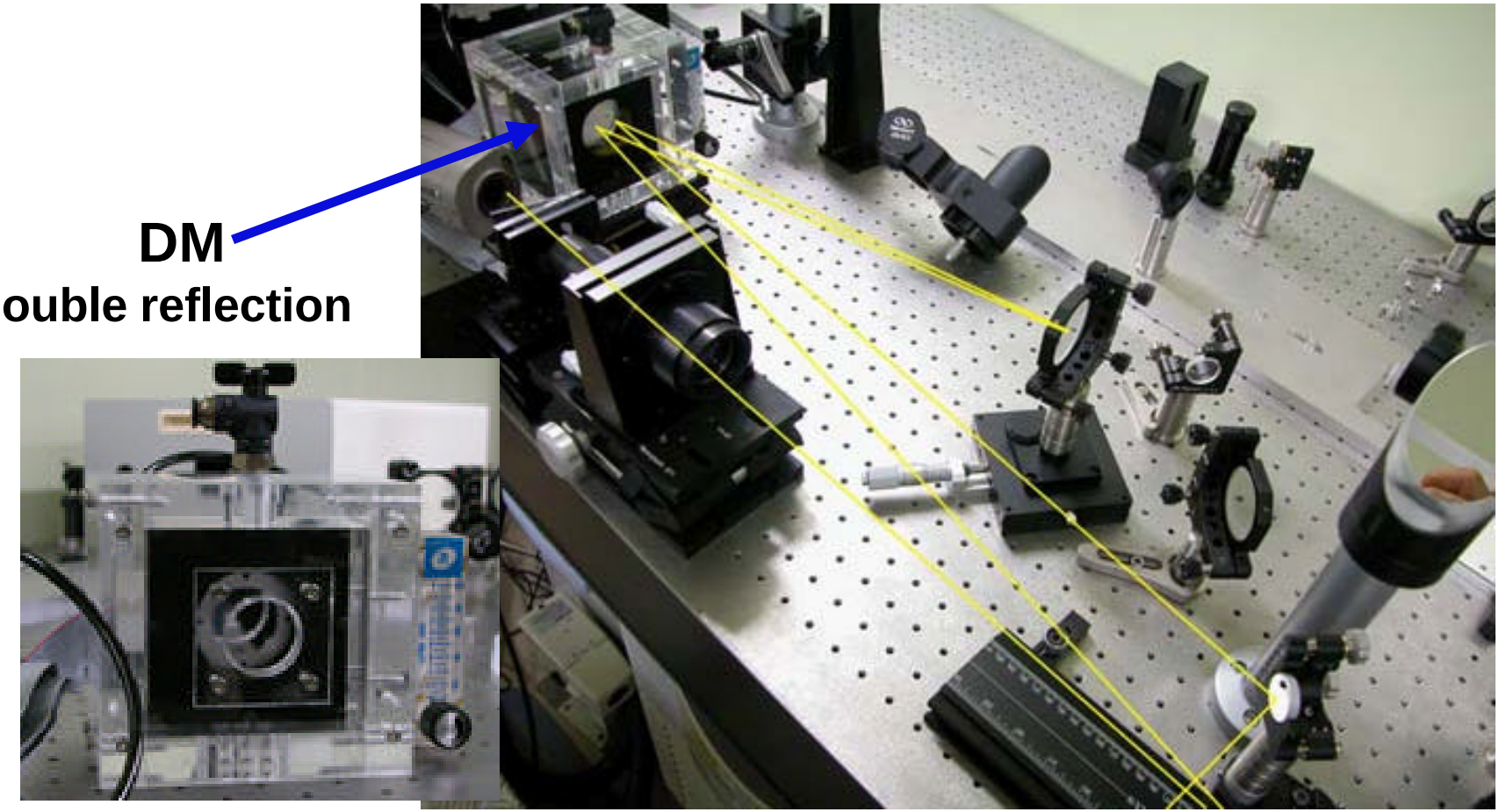
2.3.9 Spatial shaping with Deformable Mirror

Mirror cell: 59
Deformation step: 250

➔ **Combination: 250^{59} ~10^{141} !**

AI-Algorism for spatial shaping is under development

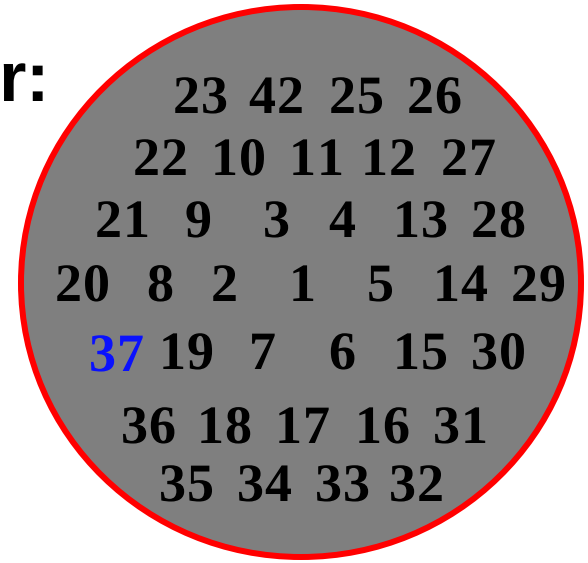
DM
Double reflection

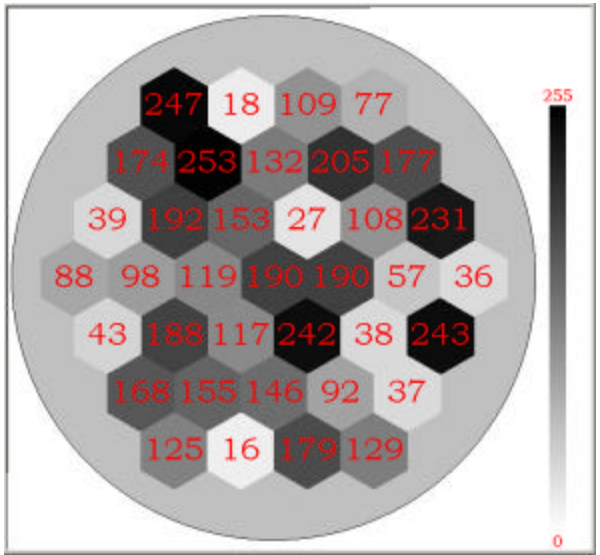


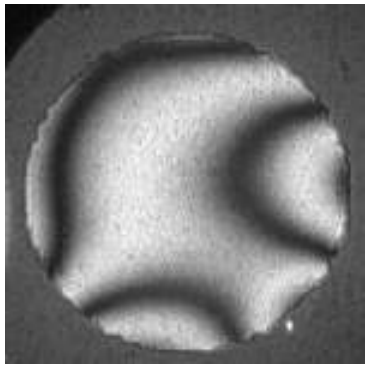
Structure of DM-Actuator:

Voltage: 0 ~ 255 V

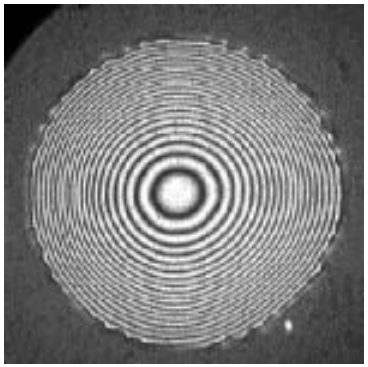
Actuator:



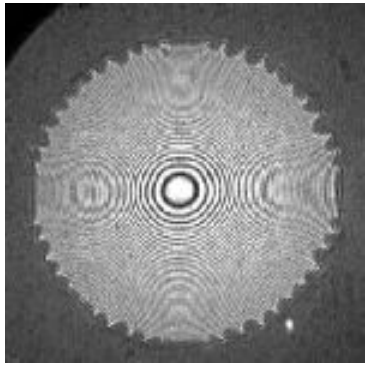




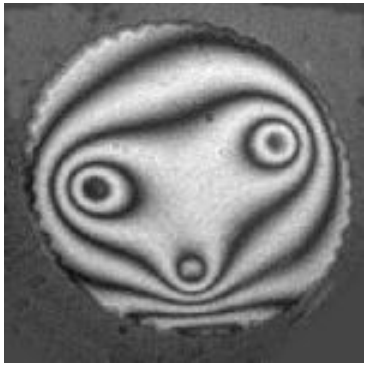
Initial State (All: 0V)



All: 125V



All: 255V (Max. Voltage)



Random Voltage

http://www.okotech.com/

2.3.10 Basic Concept of genetic algorisms

Genetic Algorithm

<Basic Process>

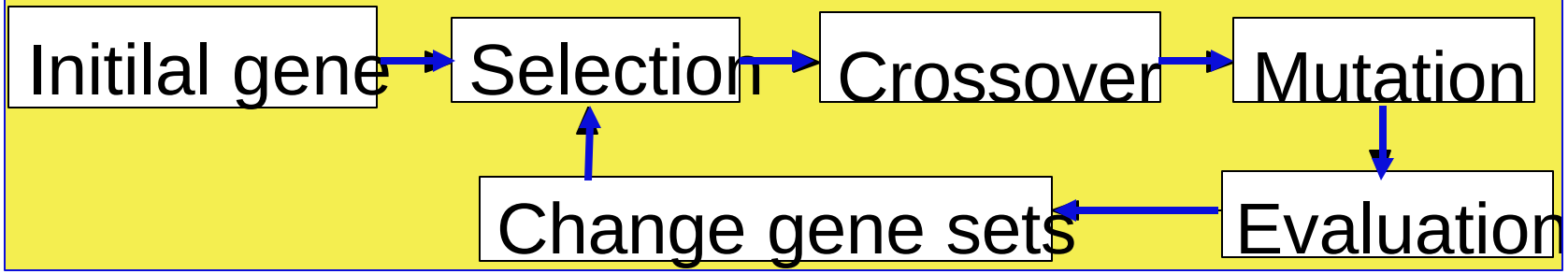
1) **Coding**: Digitize control parameters

gene

1	0	1	1	1	0	0	0

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

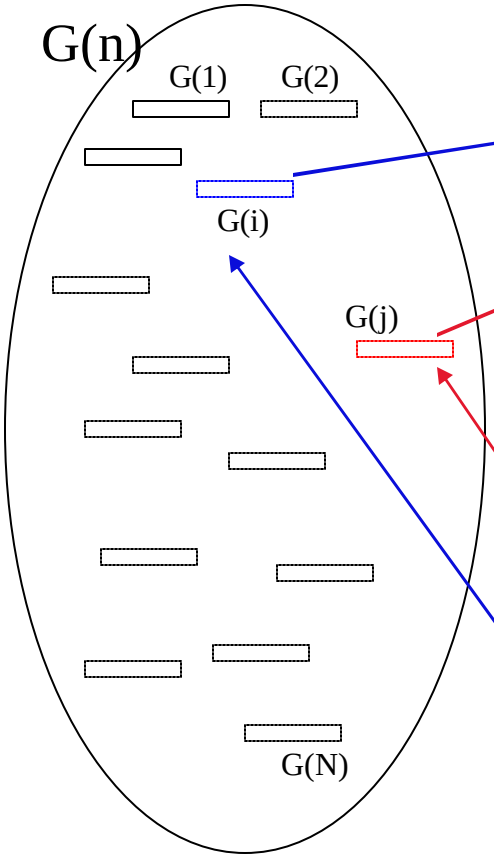
3) Basic Process



Procedure (1 step)

Chromosomes Group

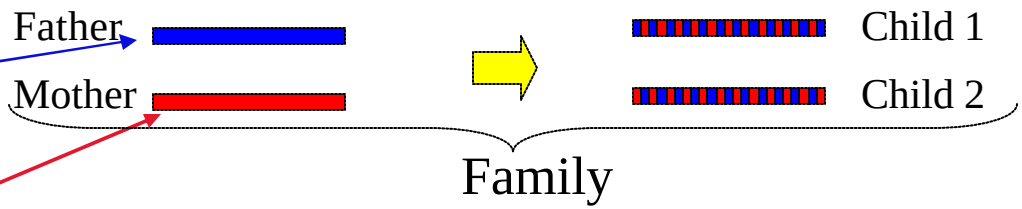
(Number: N)



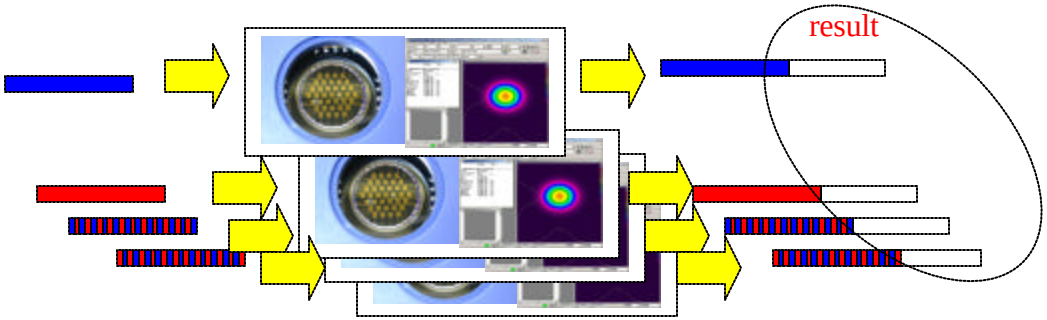
N: default

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

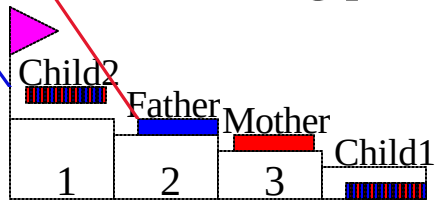
Parents (Selected randomly from G) Create 2 Children from the Parents



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



(3) Evaluate resulting parameter (Close to Flattop)



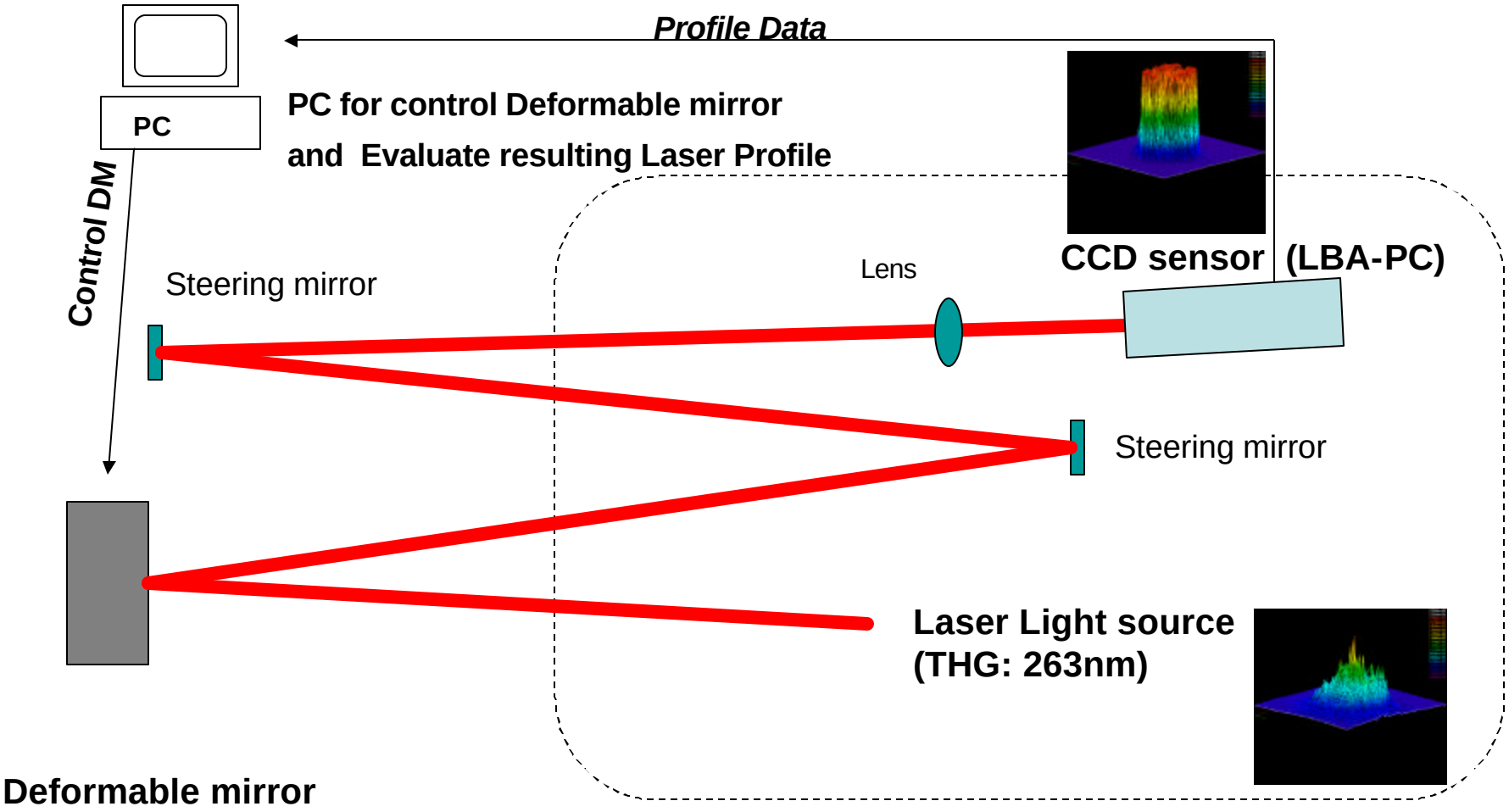
Resulted new order of priority

Child2>**Father**>Mother>Child1

Selected!

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

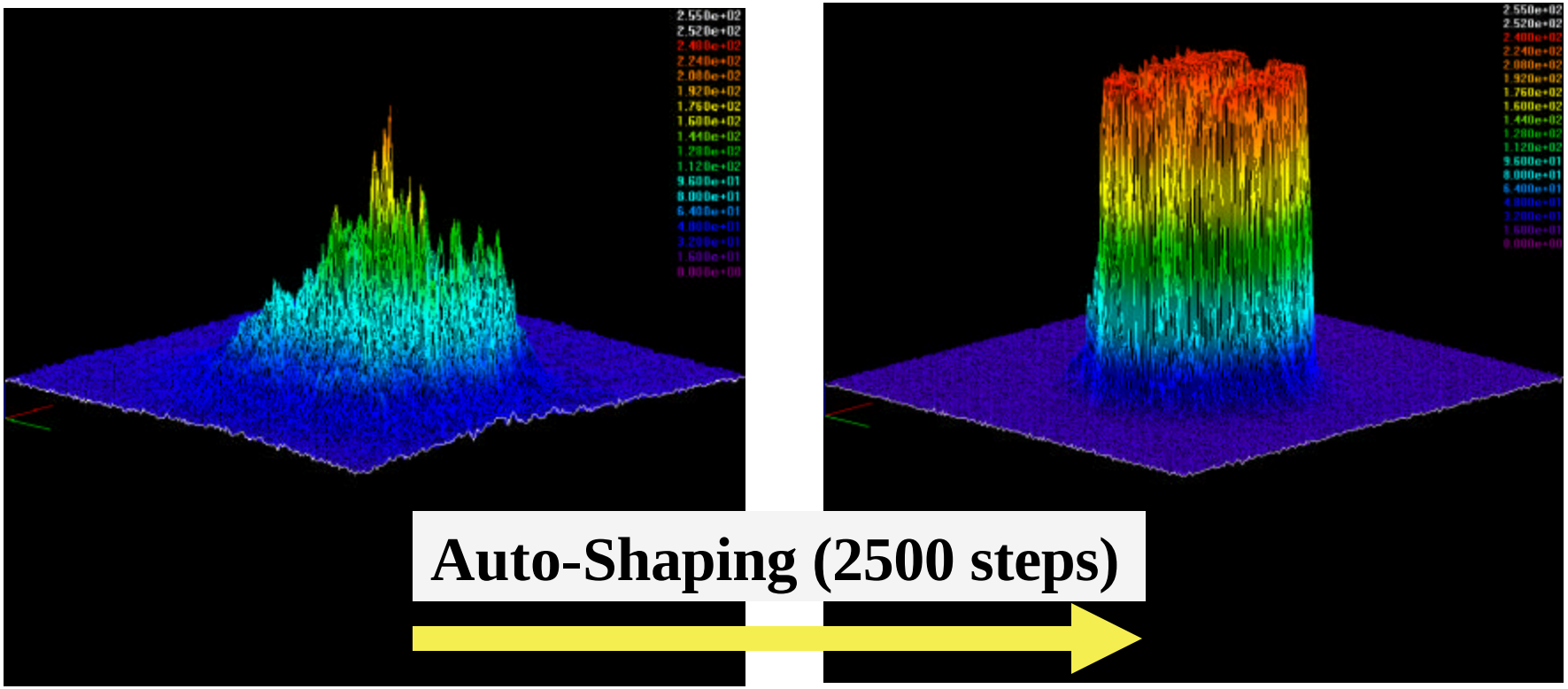
2.3.11 Closed Control System for experiment



2.3.12 Results of spatial shaping with DM

- First test for computer-aided **DM** was done with He-Ne
  → **Flattop shaping OK!**

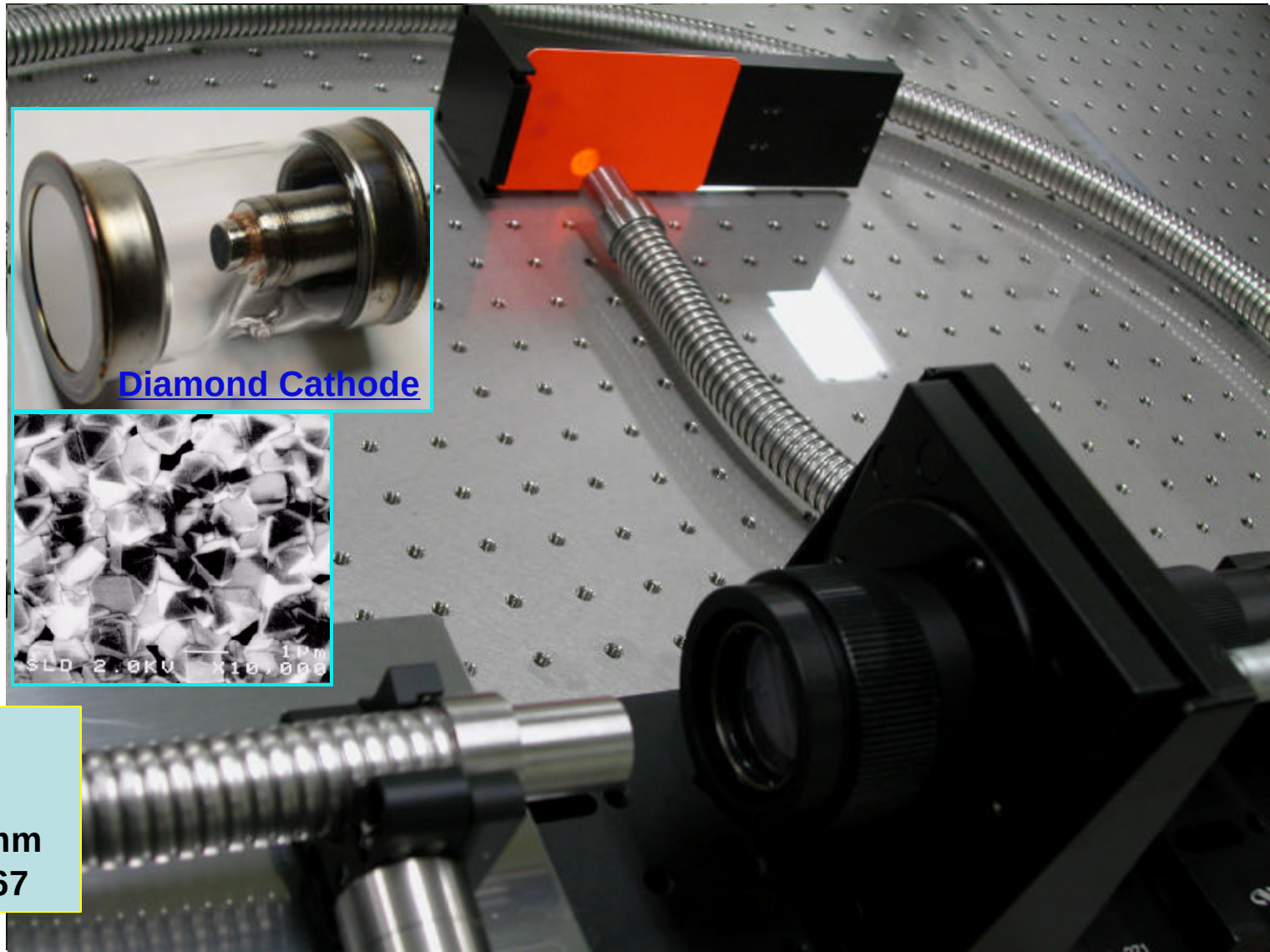
- Computer-aided **DM** for UV (THG)
  → **No problem (even for FHG:197 nm.)**



2.3.13 Both profiles shaping with Fiber Bundle

~ Transparent Cathode with Fiber Bundle ~

Pulse Stacking with 2,000 different Optical Passes



Fiber Bundle:

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

2.3.14 Results of shaping with Fiber Bundle

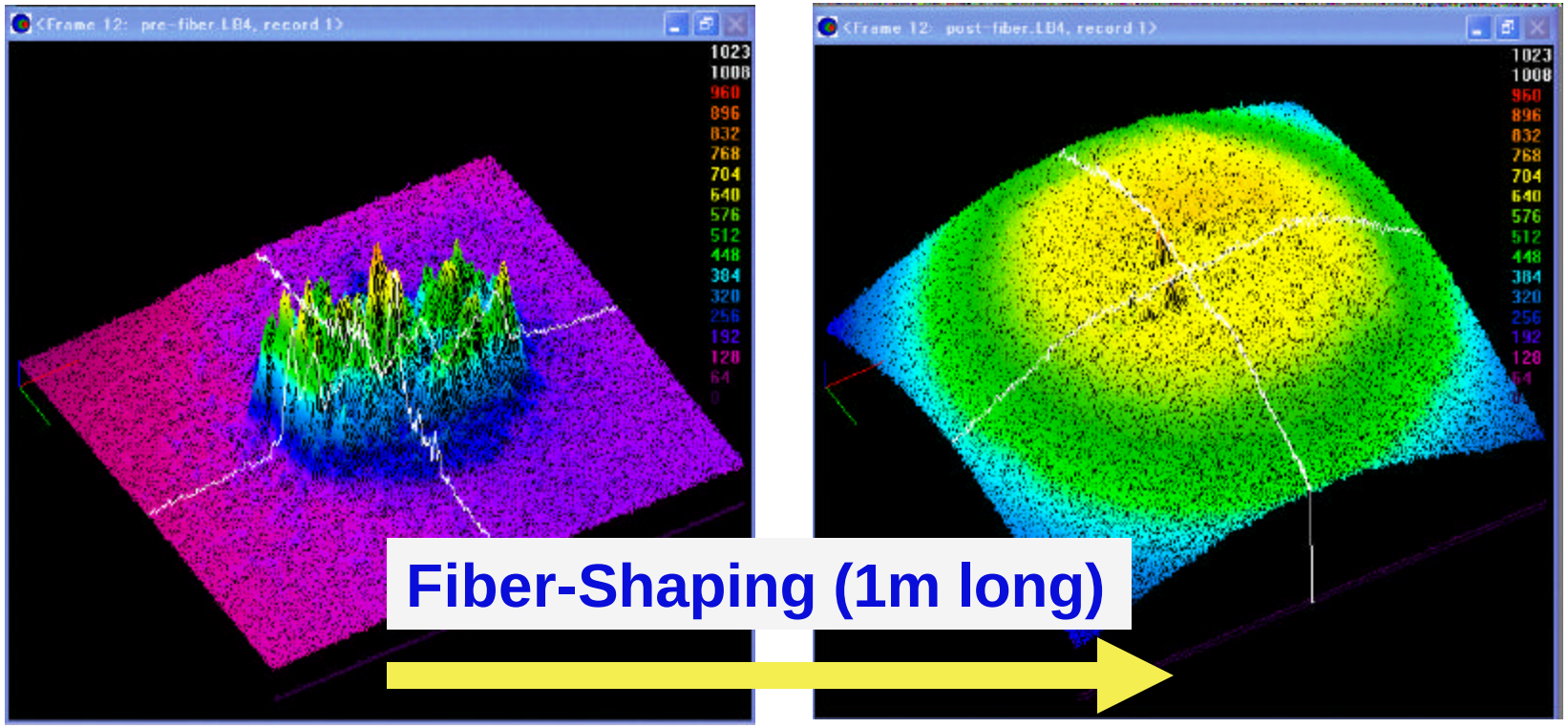
1. Results of spatial profiles with shaping

- Spatially homogenizing is very strong with FB

  → **Any kind of bad profile can be corrected!**

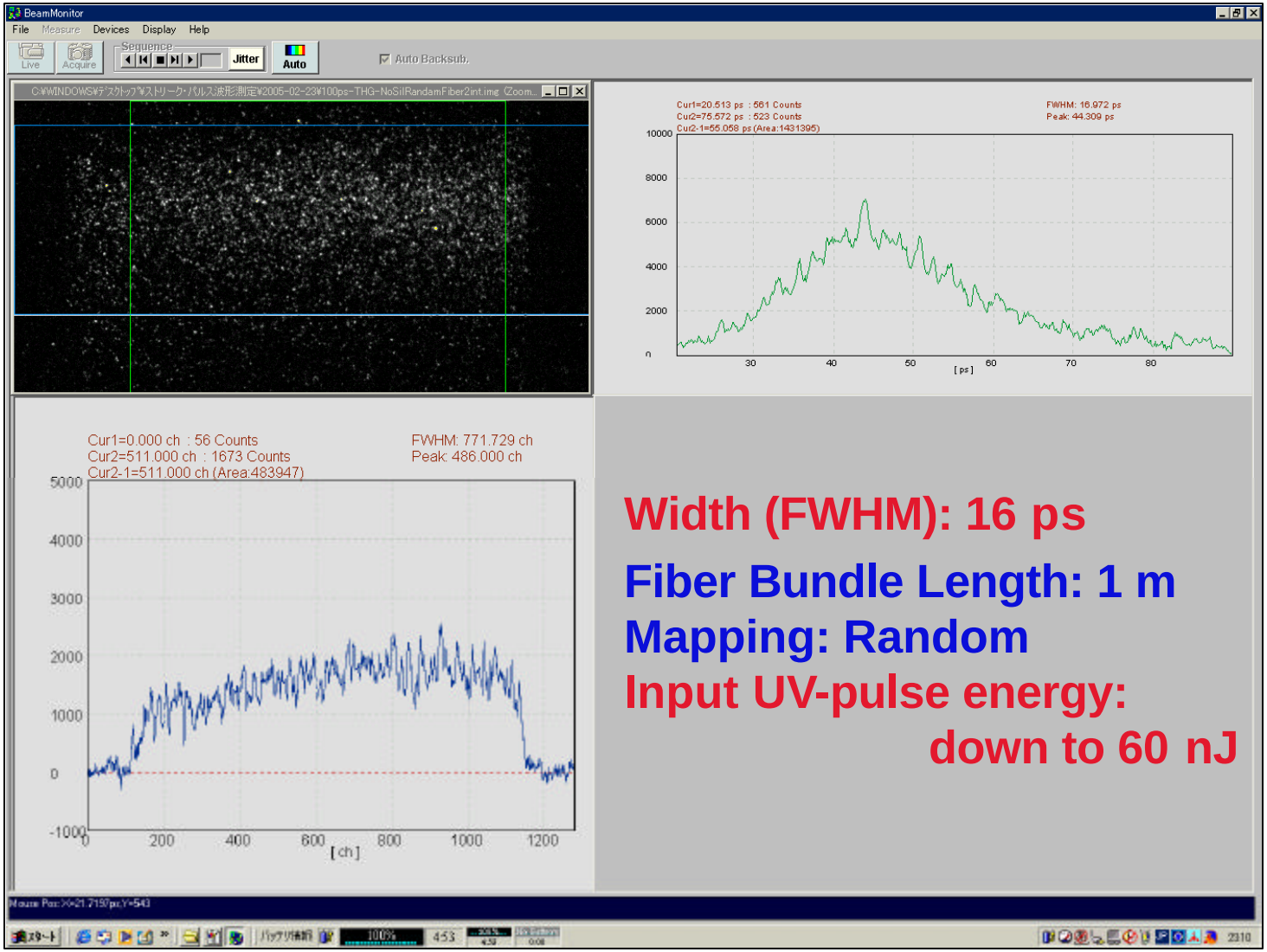
- Pulse shaping & stretching with FB is **pulse-stacking**

  → **Depend on the length and mapping of FB**



2. Results of temporal profiles with shaping

~ Pulse shaping result due to mainly Pulse Staking effect ~



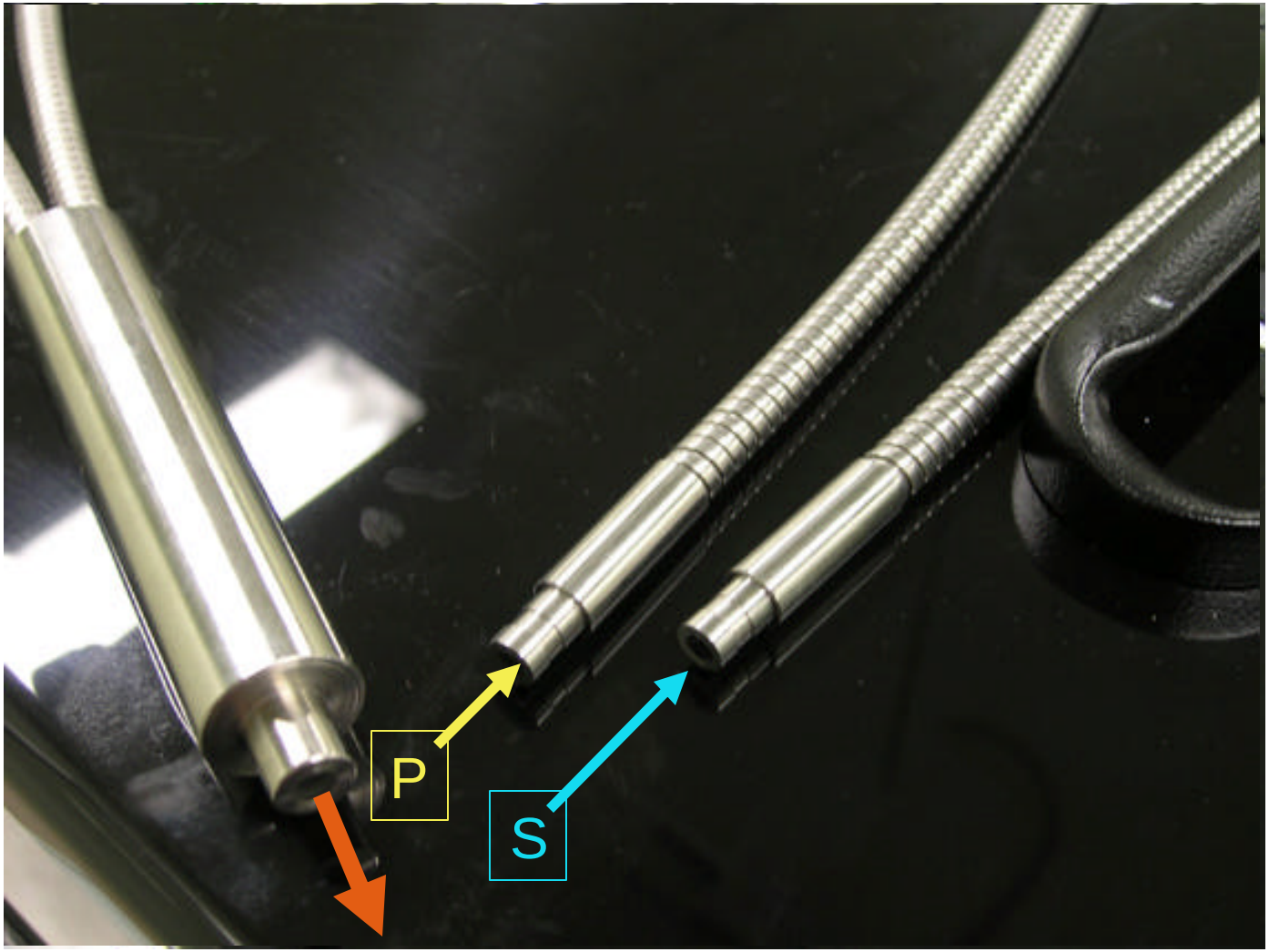
Width (FWHM): 16 ps

Fiber Bundle Length: 1 m

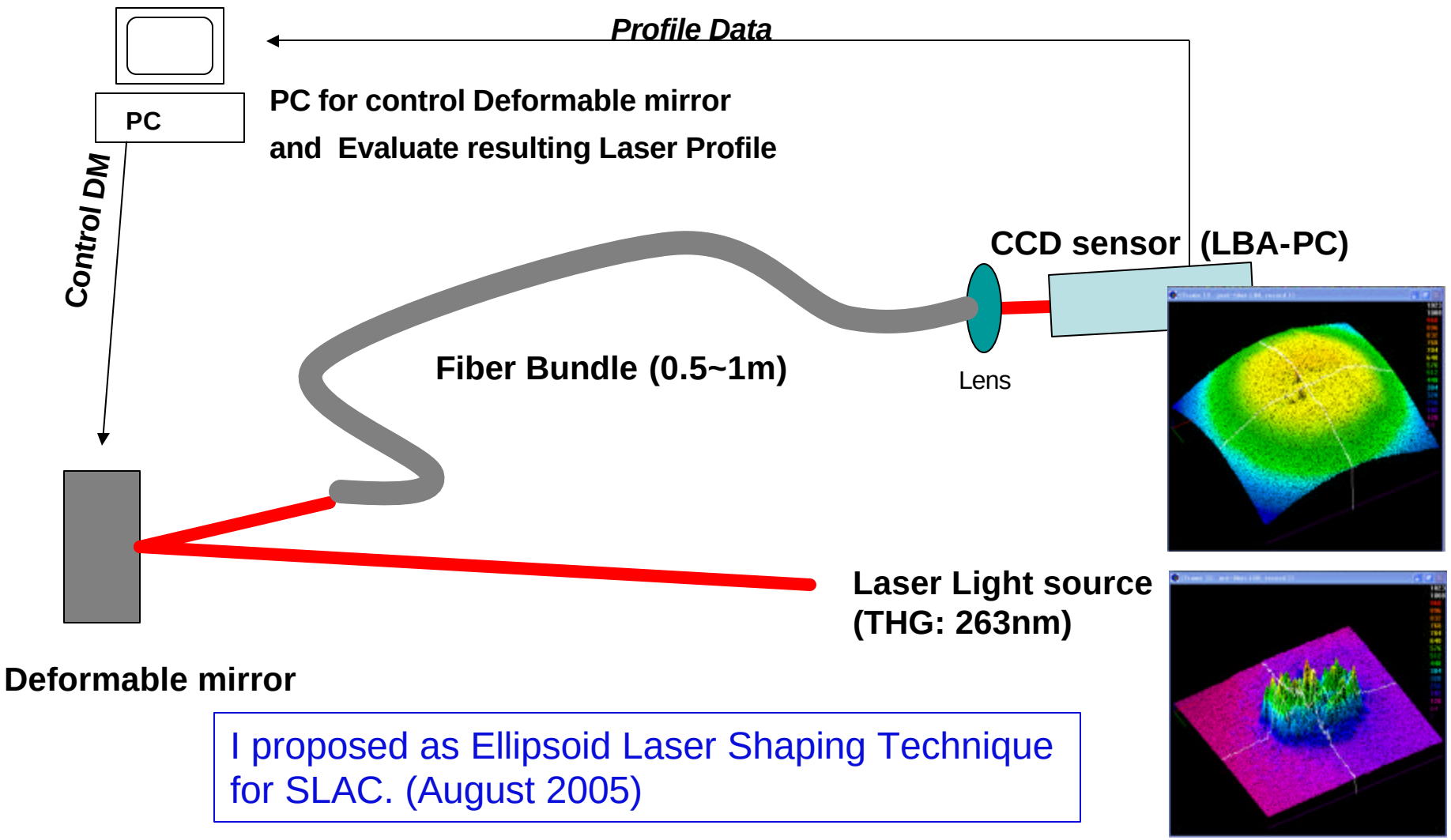
Mapping: Random

Input UV-pulse energy: down to 60 nJ

3. Avoiding interference spikes on temporal profiles



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



I proposed as Ellipsoid Laser Shaping Technique for SLAC. (August 2005)

Short Summary of Laser shaping

- Shaping with computer-aided deformable mirror could generate Flattop. It is very flexible to optimize the spatial profile 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.

2.4 Long-term stabilization of laser

1. Passive Stabilization (completed)

Stabilizing **environmental & mechanical** factors

⬇

Reduction of**:**

- Optical damaging accidents

- Mechanical instability of optical components

2. Active Stabilization (in coming year)

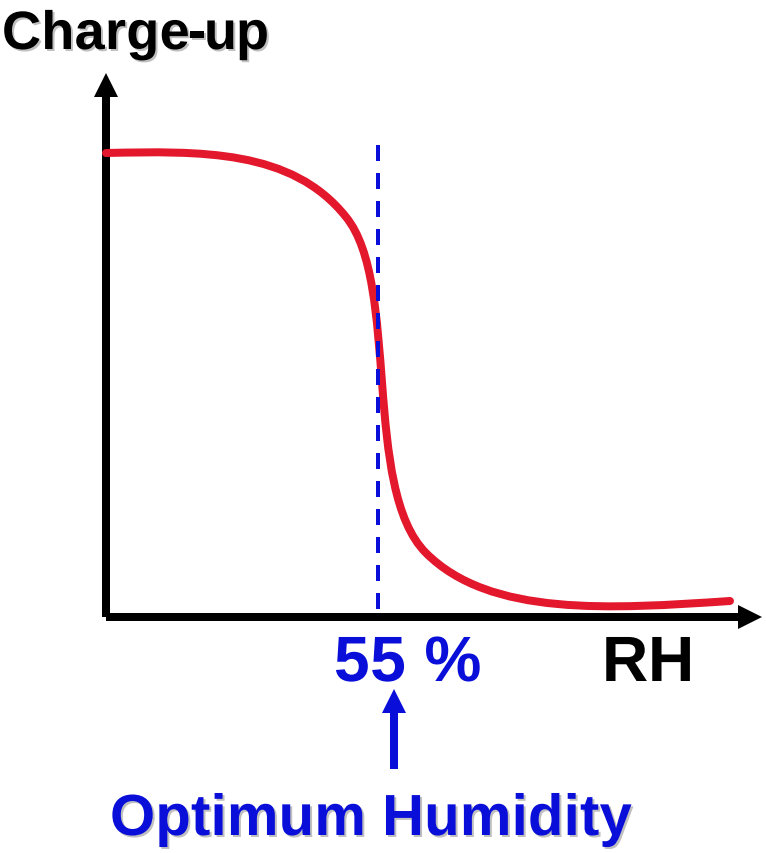
- Automatic **boot-up**
- Automatic **adjustment** (AI-algorism)
- Automatic **Flash Lamp control** (Long-term Drift)
- Automatic **Re-gen Energy control** (shot-by-shot)

3. Down-Sizing (in future)

2.4.1 Humidification for avoiding charge-up

Environmental test clean room

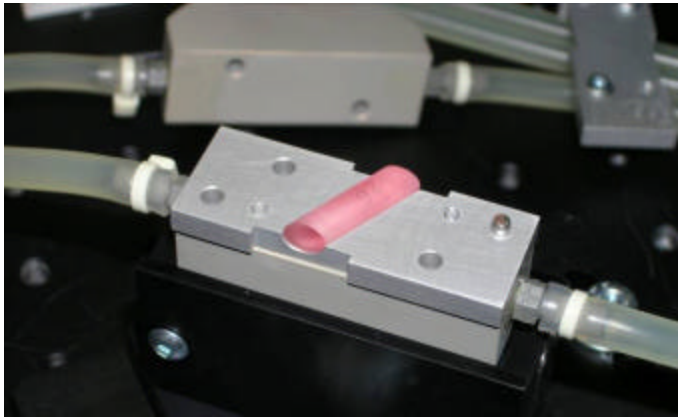
Constant Temperature & Humidity



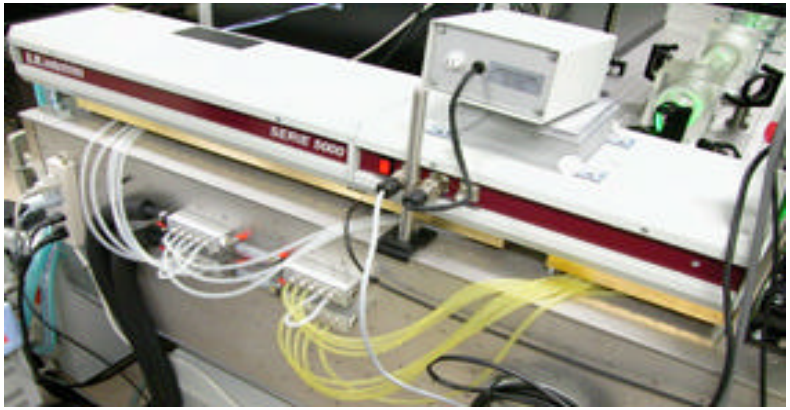
2.4.2 Long-term stabilization with water-cooling

5 ~ 10 % (rms) **After Passive control** → **@THG (263 nm)** *0.7 ~ 1.3 %* (rms)

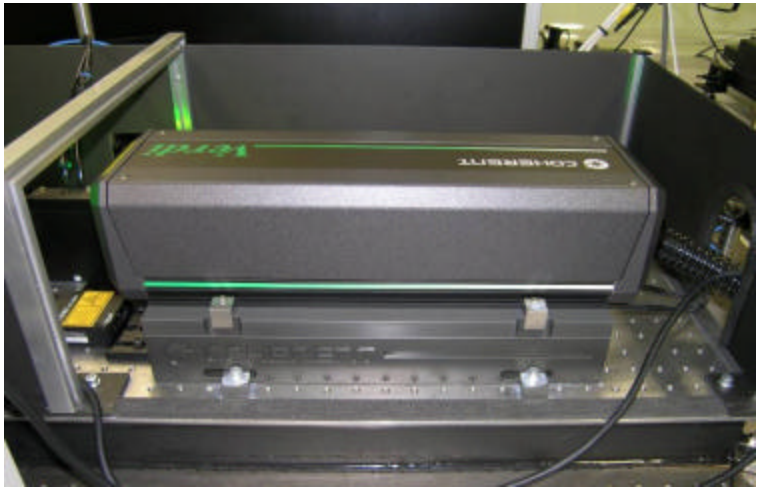
Water-cooling for crystal
Suppress thermal lens effect:



Water-cooling for base-plate
Fix deformation of laser-box:

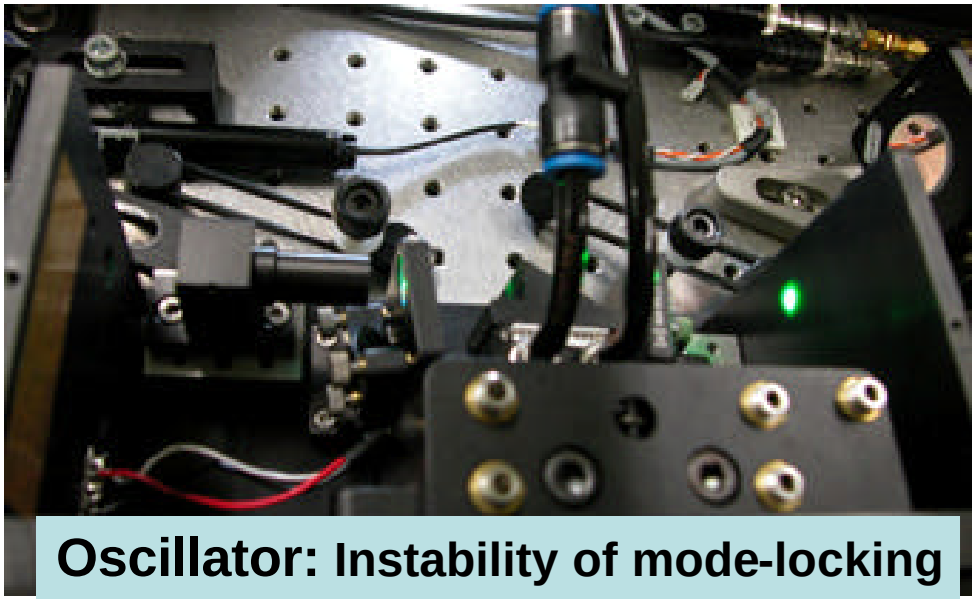


Water-cooling for Pockels Cell:
Suppress local heat-up:



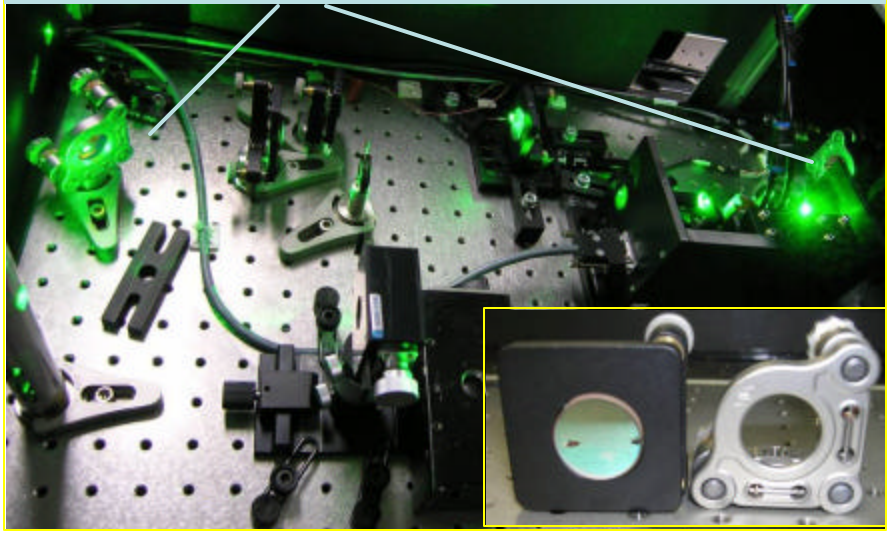
2.4.3 Passive & Active stabilization of Oscillator

The most critical part of total laser stability



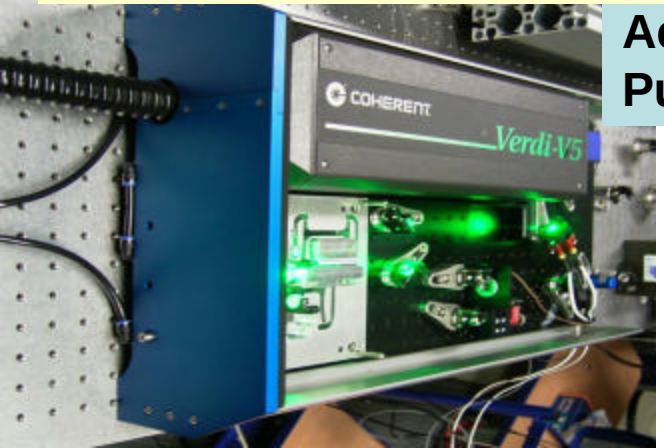
Oscillator: Instability of mode-locking

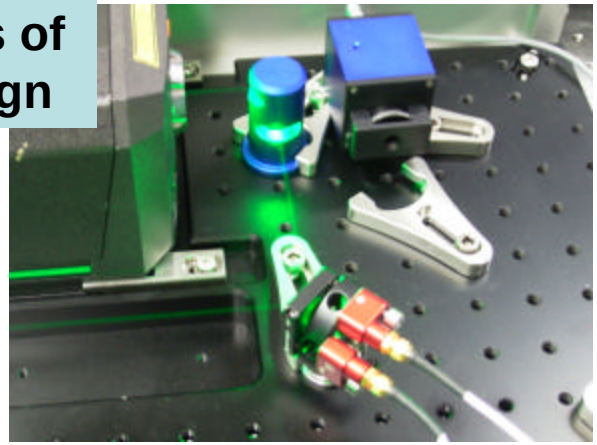
Replace conventional mirror holders with the thermal-deform-free ones.



New Oscillator is preparing

Active controlling optical pass of Pumping light source: Autoalign





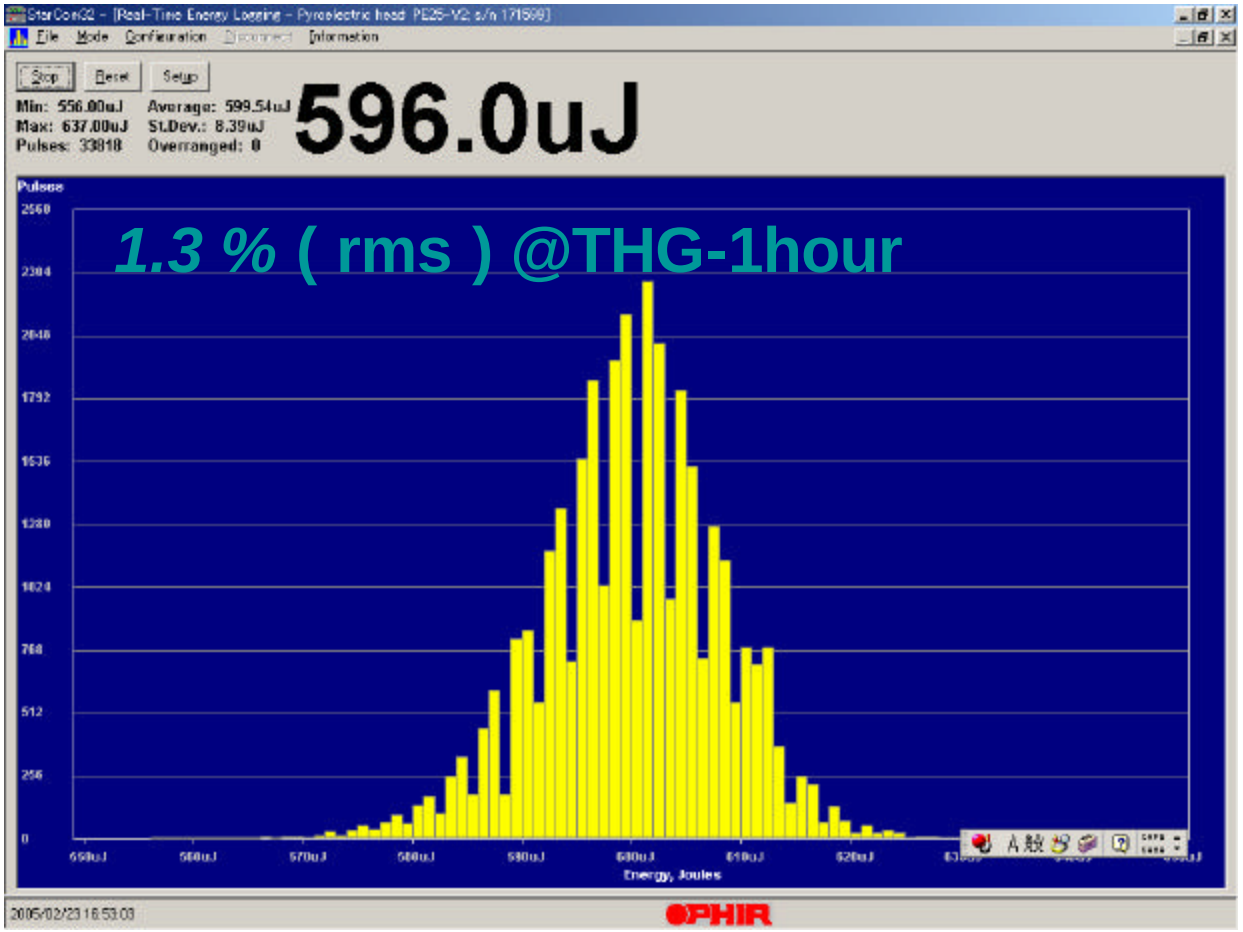
2.4.4. The present status of stability of UV-Laser Light Source

Present UV-laser stability:

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

Long Term:
1 Month
continuously

With new Oscillator, it will be 2 months.



After Passive control

5 ~ 10 % **(rms)** → ***0.7 ~ 1.3 %*** **(rms)**

2.4.5. The plan of stabilization of UV-Laser Light Source

2003

1 . Complete environmental control

Temperature, Humidity(RH: 55 %)

New Clean Room & Optical Table

2004

Summer

2 . Long-term stabilized Maintenance-free

Laser light source was available!

passive

active

2004

Winter

3 . Realize Automatic Spatial & Temporal

Shaping, Adjustment of Laser

2005

4 . Active stabilized Auto-Start-up

Laser light source will be available!

3. Cavity & Laser incidence

3.1 Pillbox cavity

3.2 Results of Emittance Measurement

3.3 Effects of oblique incidence of a laser

3.1 Single-cell Test Cavity (First beam in 1999)

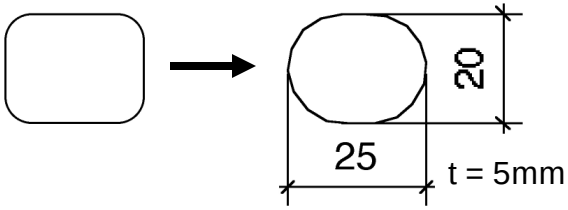
- Low Q (Q ~2800 ← 200MV/m@80MW)

  $1/Q = 1/Q_0 + 1/Q_{ext} = (P_0 + P_{ext})/\omega U$

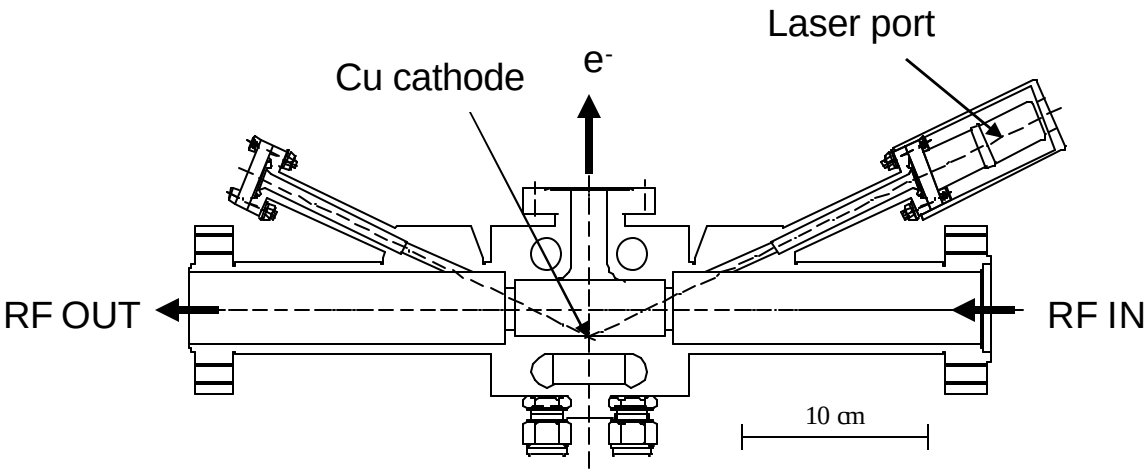
  Shorter RF Pulse → Higher Field Gradient

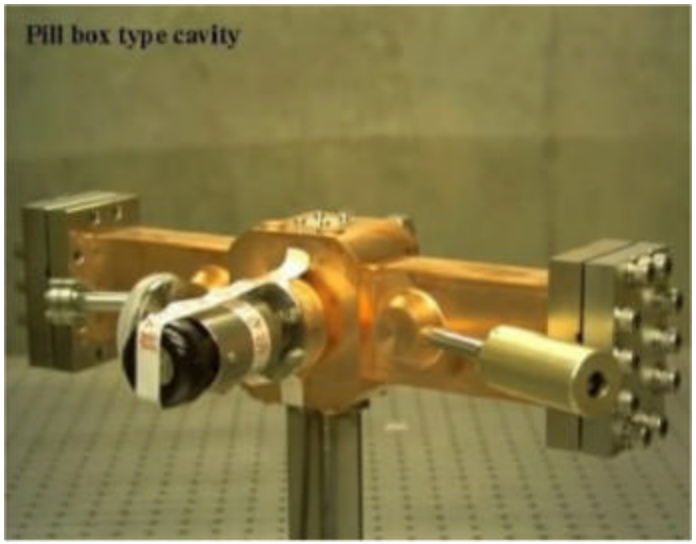
- Round and Thick Coupler Hole

  Relaxation of surface current concentration



- Pure Water Rinsing → Dark Current Reduction





3.2 Results of Beam Emittance Measurement

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

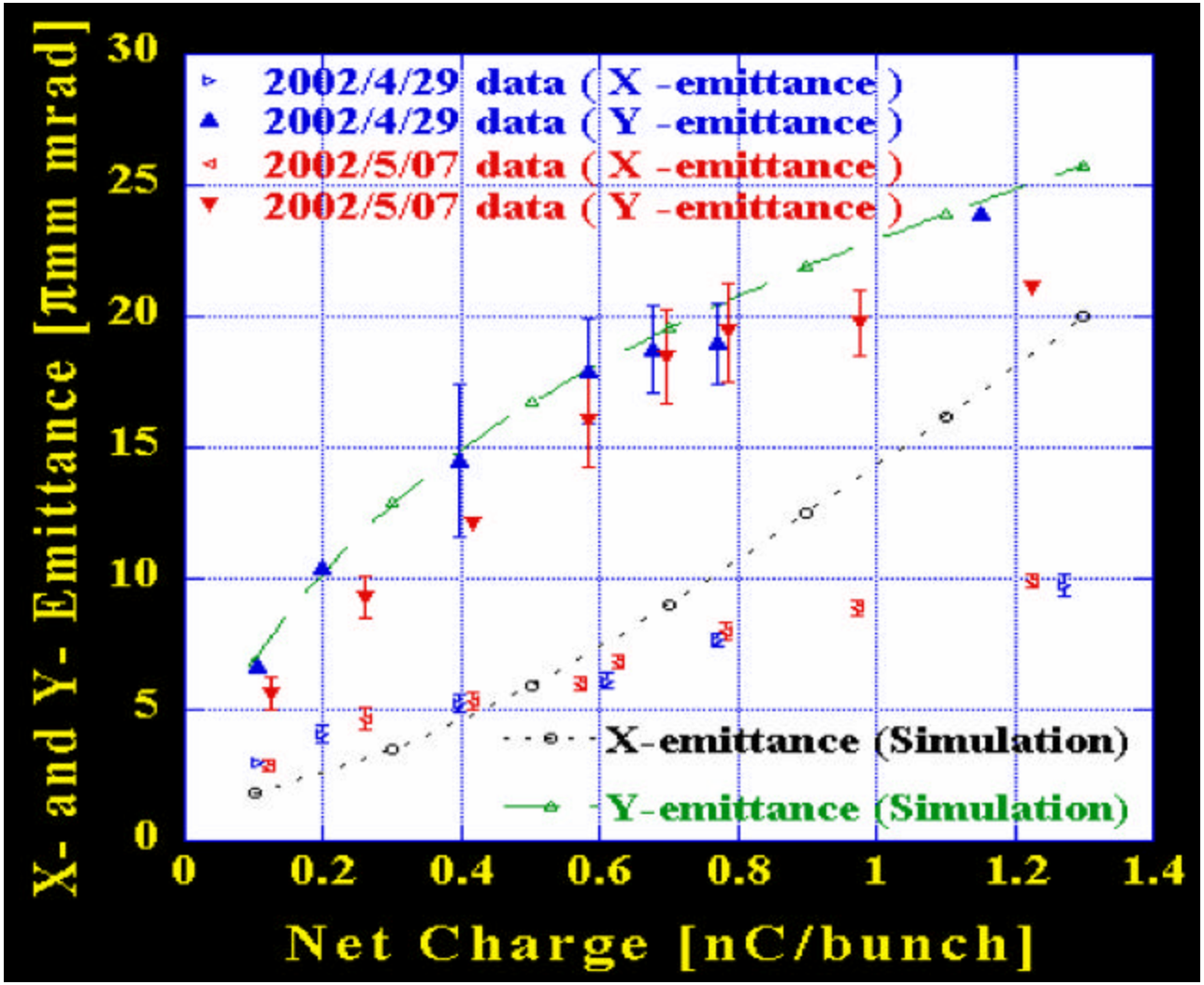
6.0 p mm mrad

May 2001

Laser S-Profile Improvement

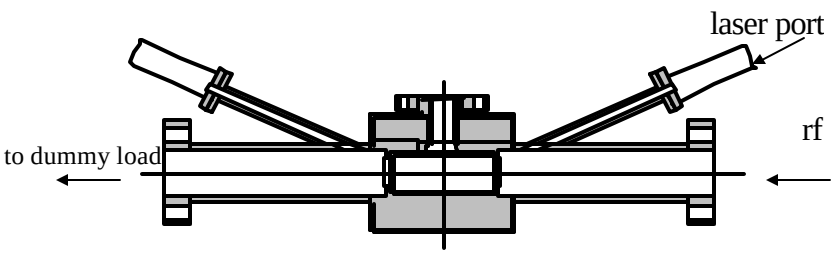
2.3 p mm mrad

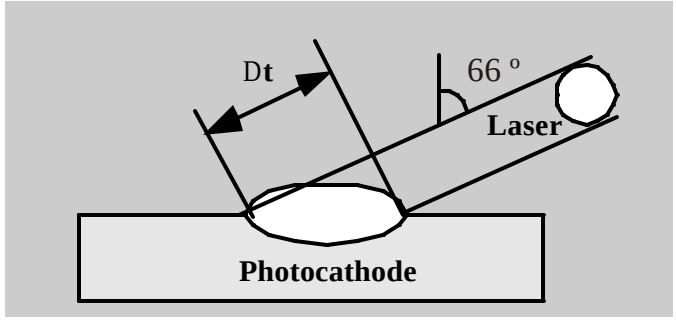
After Dec. 2001



(Under Construction and Laser Replacement: 2002 ~2004)

3.3 Effects of oblique incidence of a laser to the cathode



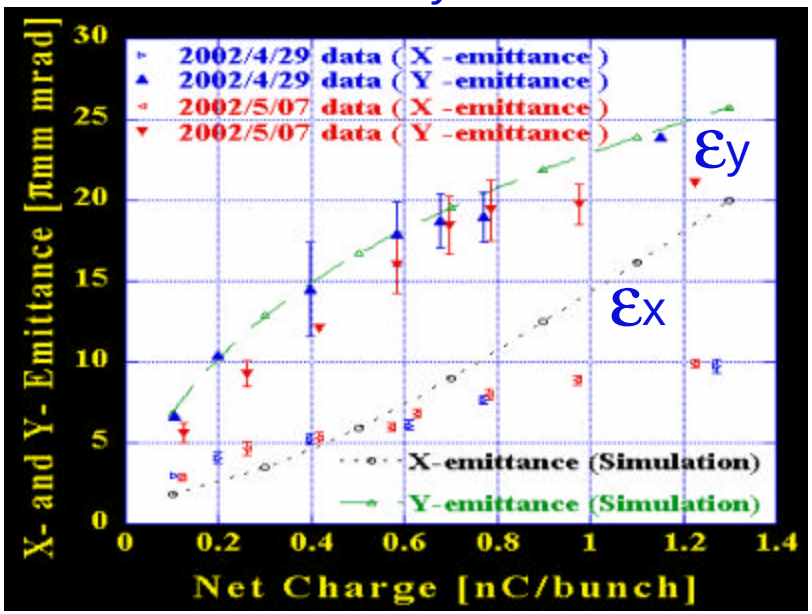


Time delay & elliptical laser shape

$\varepsilon_x < \varepsilon_y$

Parameters (for both experiment & our simulation code)

- Maximum field on the cathode: **135 MV/m**
- Initial RF phase : **85 degree**
- First solenoid coil : **1560 Gauss**
- Second solenoid coil : **780 Gauss**
- Laser incident angle : **66 degrees**
- Laser spot distribution: **Gaussian like figure**
- Laser spot radius : **0.3 mm (1s)**
- Laser temporal length: **5 ps (FWHM)**



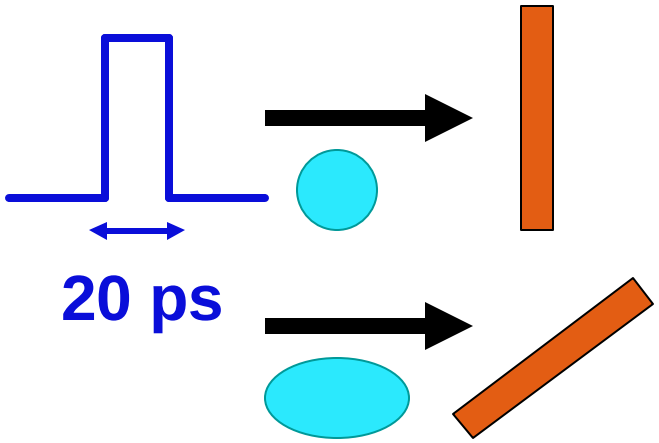
Lowest x-emittance value of 2.3 πmm•mrad was measured

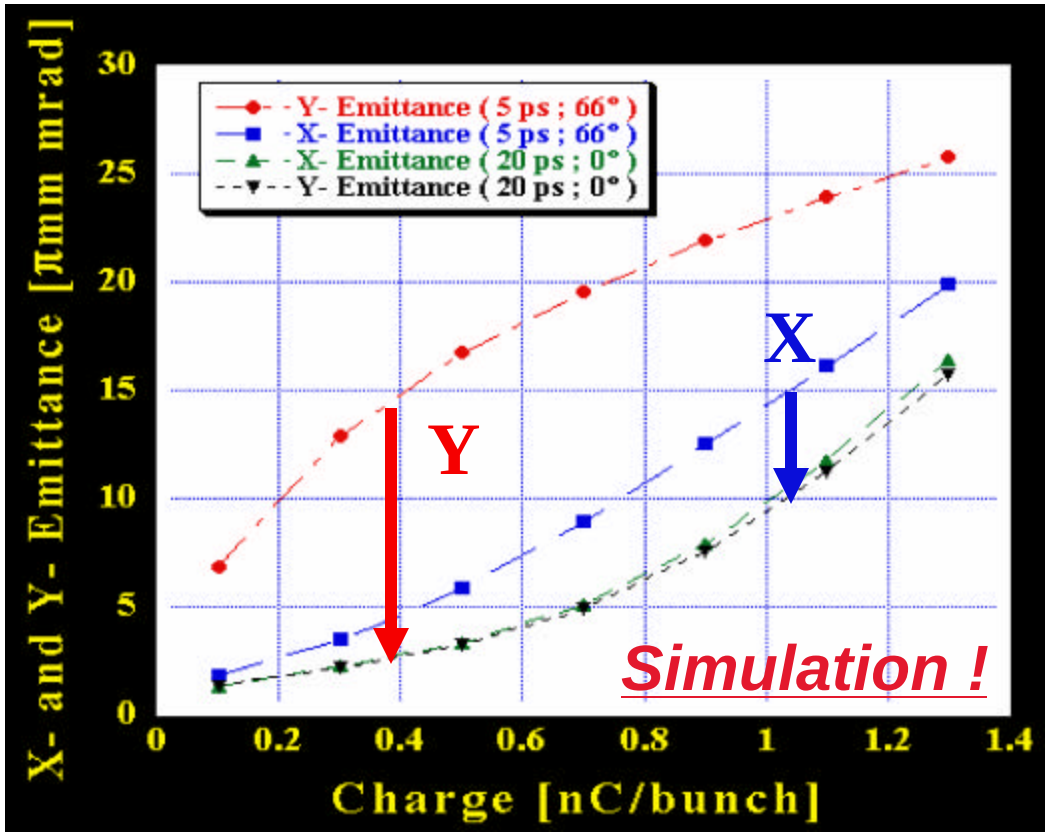
3.4 Improvement with normal incidence of a laser to the cathode

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!**

? **Perpendicular Injection!**

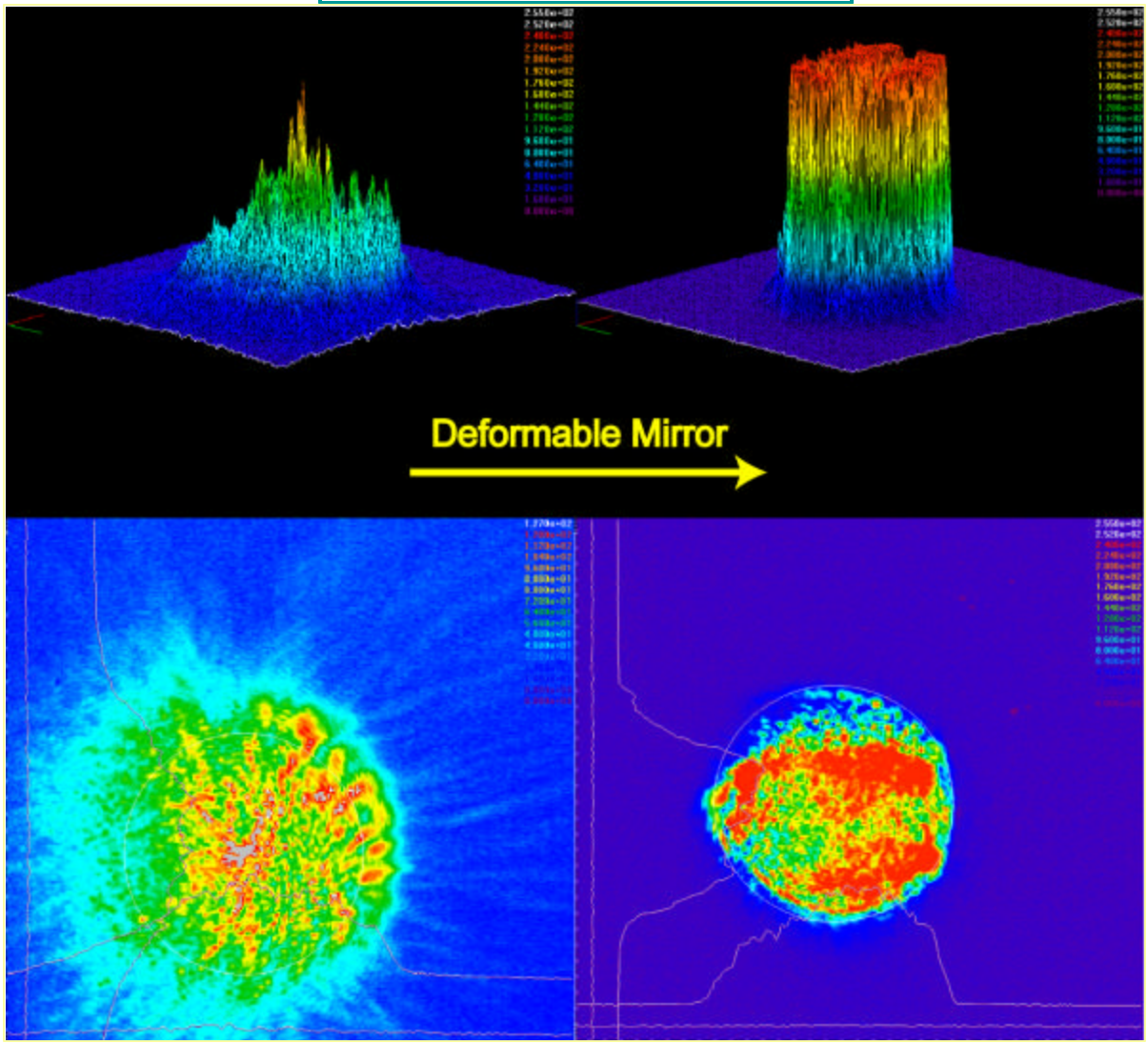




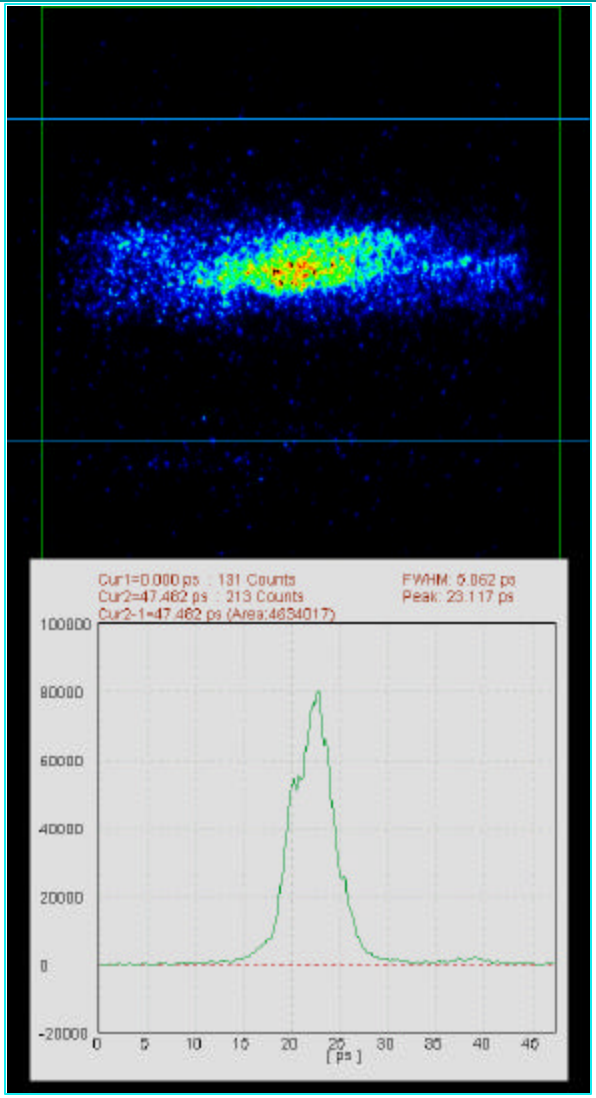
3.5 Experiment with normal incidence

1. Laser 3D-shape

Flattop with DM



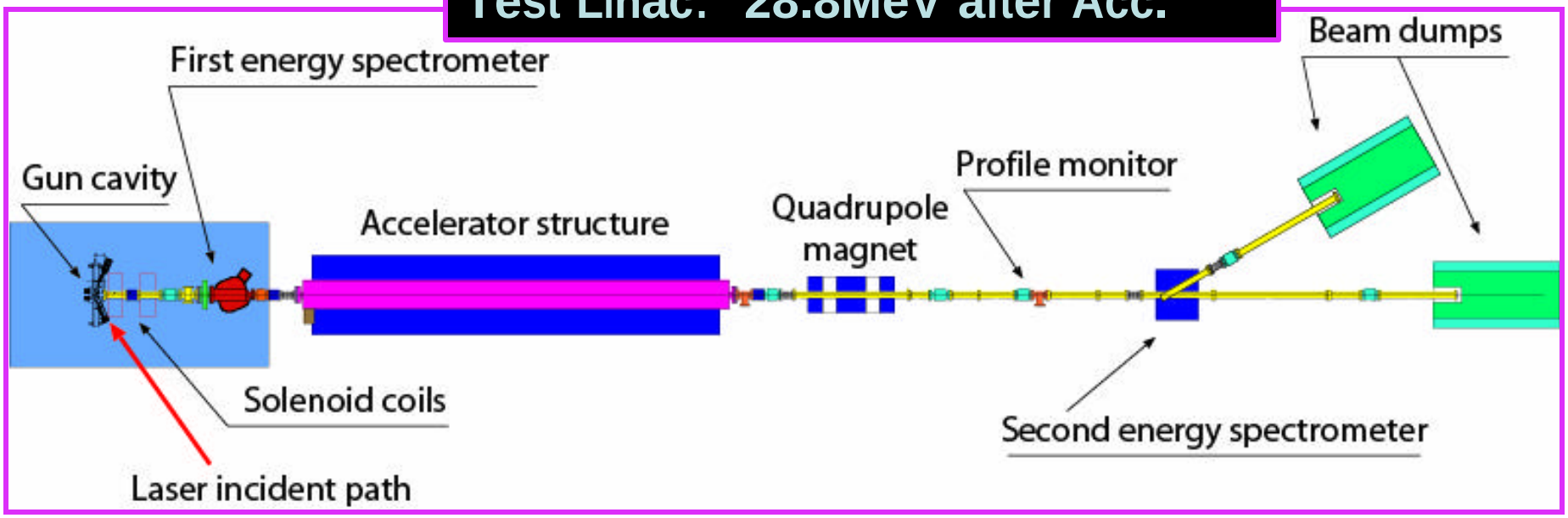
Pulse Width: 5 ps

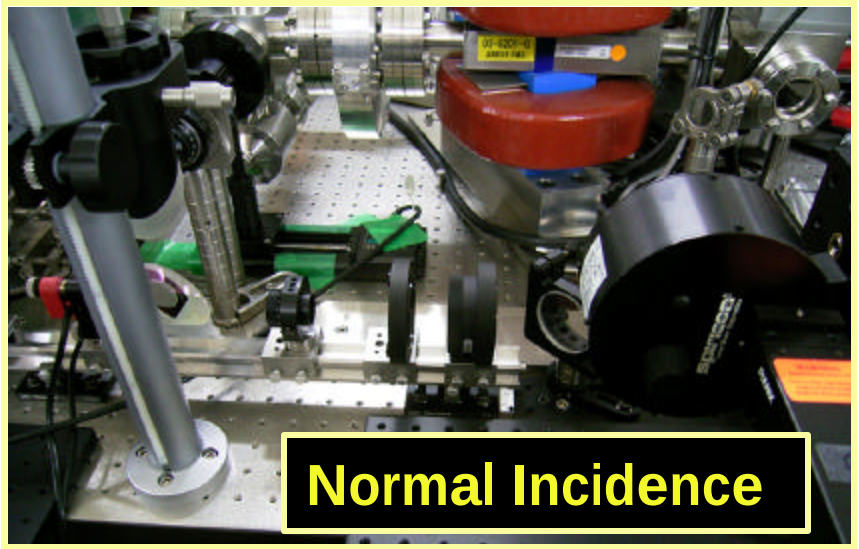


3.5 Experiment with normal incidence

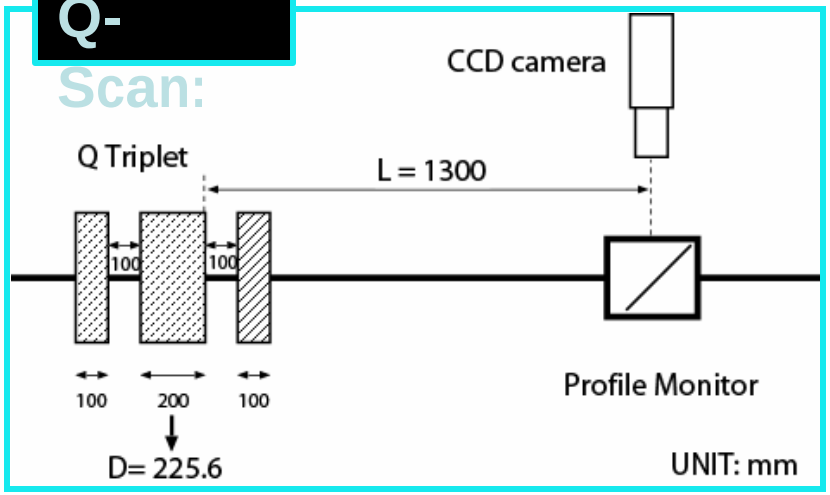
2. Experimental setup

Test Linac: 28.8MeV after Acc.



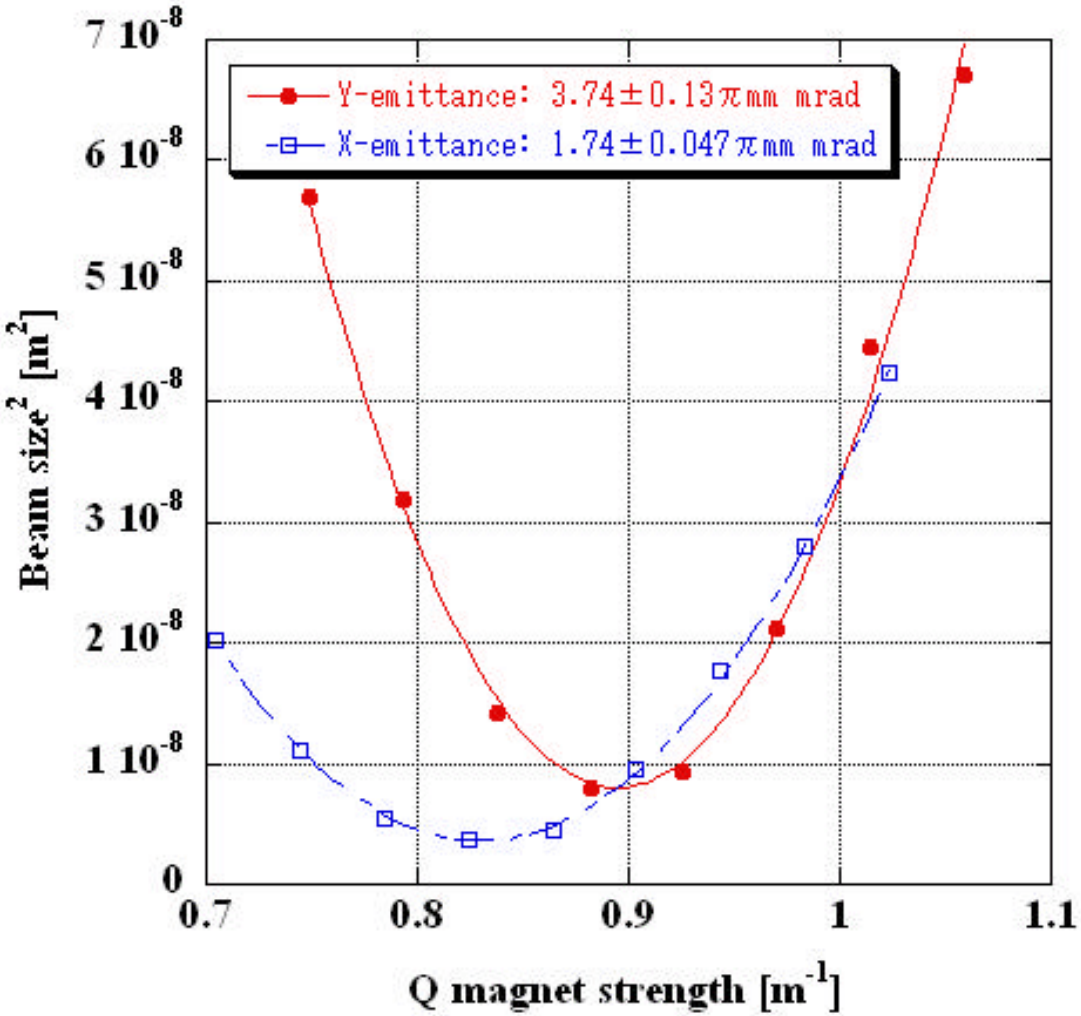


Q-Scan:



3.5 Experiment with normal incidence

3. Experimental result



Net Charge: 0.09 nC

@28.8 MeV

Profiler:
Kodak; Lanex

There is the difference between X- and Y- emittannce !

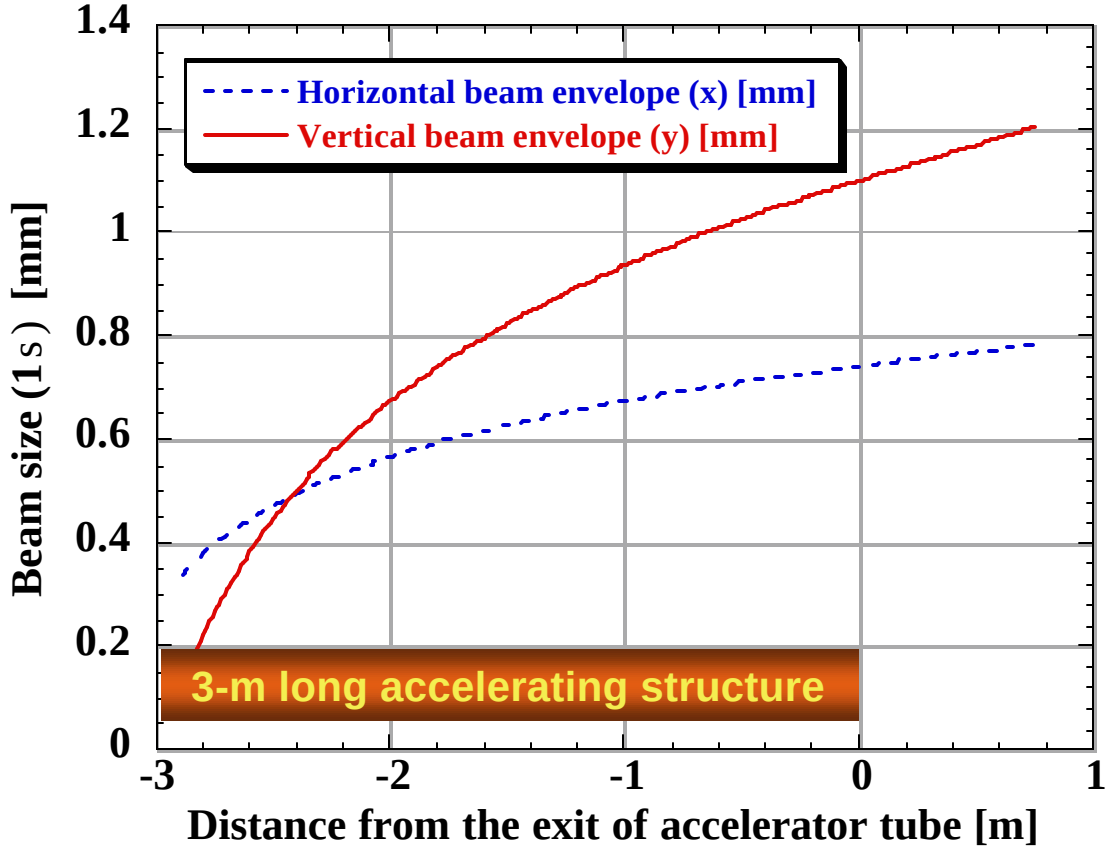
Pulse width is far from the optimum value: 5 ps

3.5 Experiment with normal incidence

4. Why different?

- We calculated back the beam envelopes with using the transfer matrix of the accelerating structure and the Twiss parameters at the quadrupole magnet.

→ **The misalignment of electron beam at the entrance of accelerating structure.**
(Asymmetrical rf focusing forces in the input coupler)



4. Surface Treatment

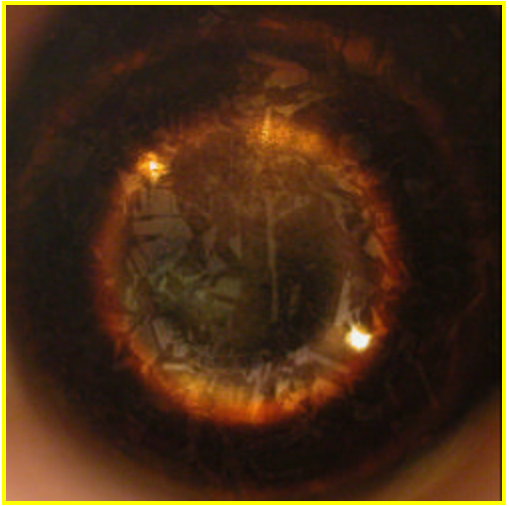
- 4.1 Motivation of Surface Treatment
- 4.2 Chemical Etching
- 4.3 Chemical Etching with Cu-test pierce
- 4.4 Experimental Results
- 4.5 Etching-processed RF-gun cavity
  & High Field Test
- 4.6 Surface Diagnosis with Cartridge-type
  Cathode System (Transparent Cathode)
- 4.7 Diamond Cathode

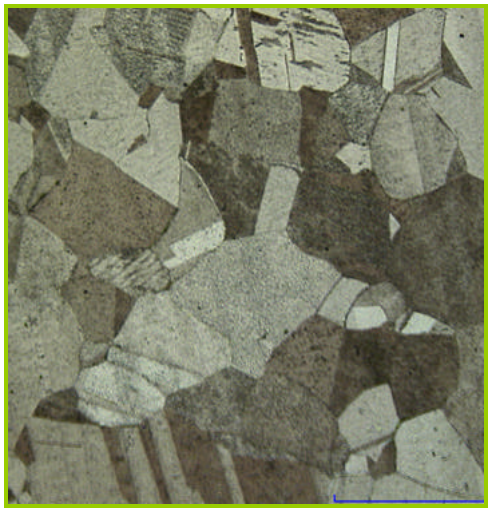
4.5.1 Etching Process of RF-gun cavity

Chemical Etching ? Cleaning cathode surface
No contamination
Least surface roughness

For high-field acceleration & high QE

Etching process



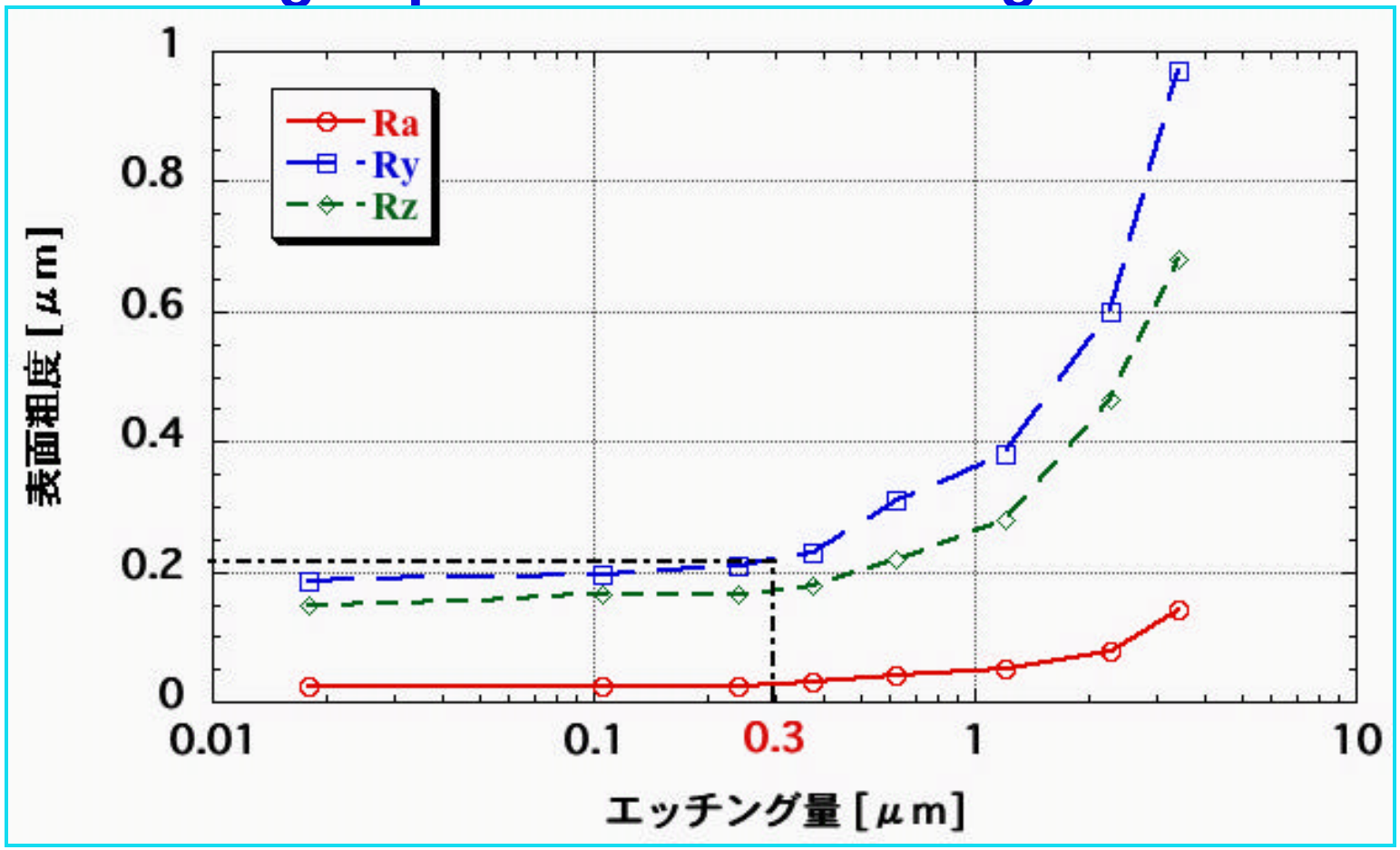


Cathode surface of RF gun after etching process

4.5.2 Chemical Etching test

H_2SO_4 & H_2O_2

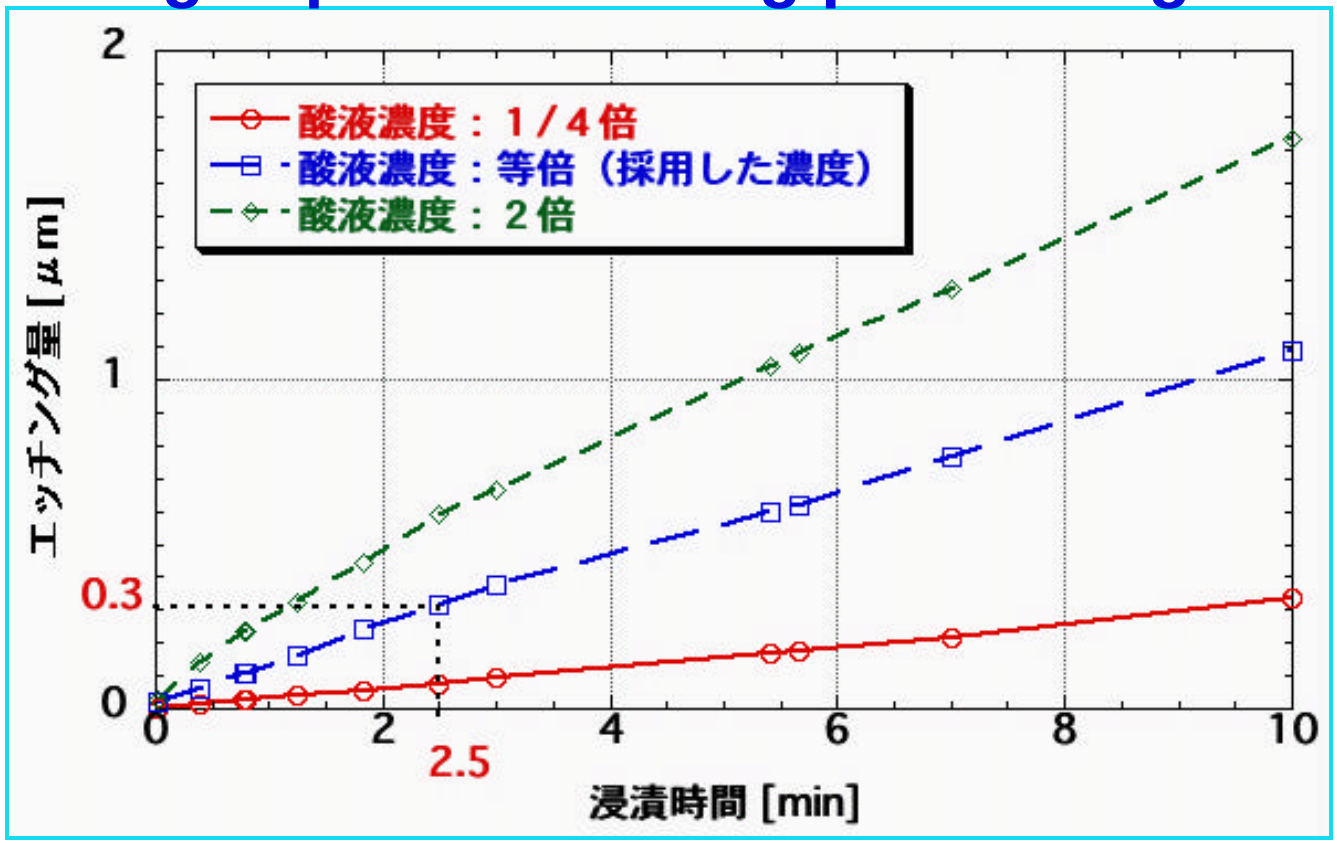
Etching depth vs. Surface Roughness



Below etching depth **0.3um**, Surface Roughness does not change!

H_2SO_4 & H_2O_2

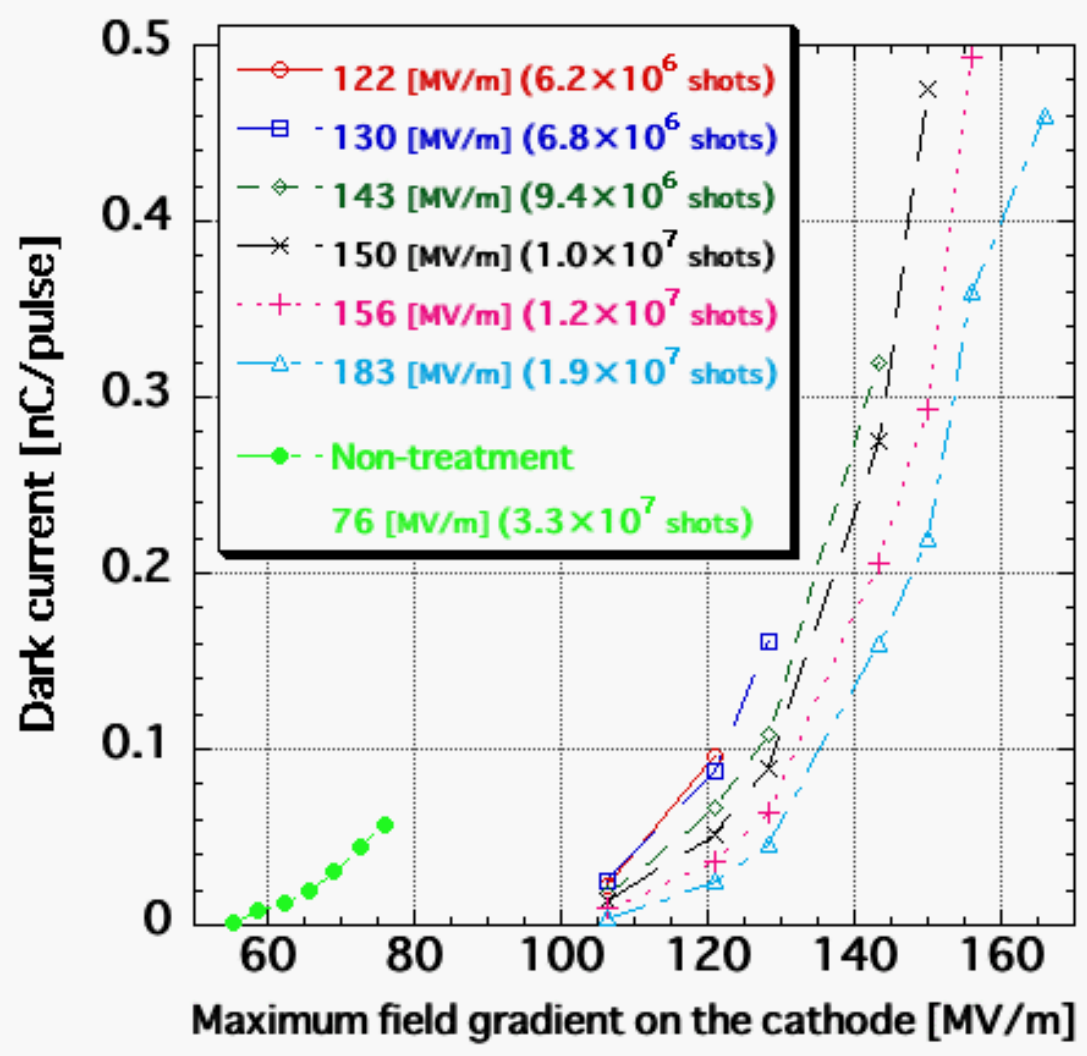
Etching depth vs. Etching processing time



Structure: Below etching depth **0.3um (2.5 min)**, Surface Roughness is reproducible. Laser microscope

Contamination: We checked no chemical contamination on the surface with FTIR.

4.5.3 High Power Test for Etching-processed RF-gun cavity



QE: 1 x 10^{-2} % (Cu-cathode)

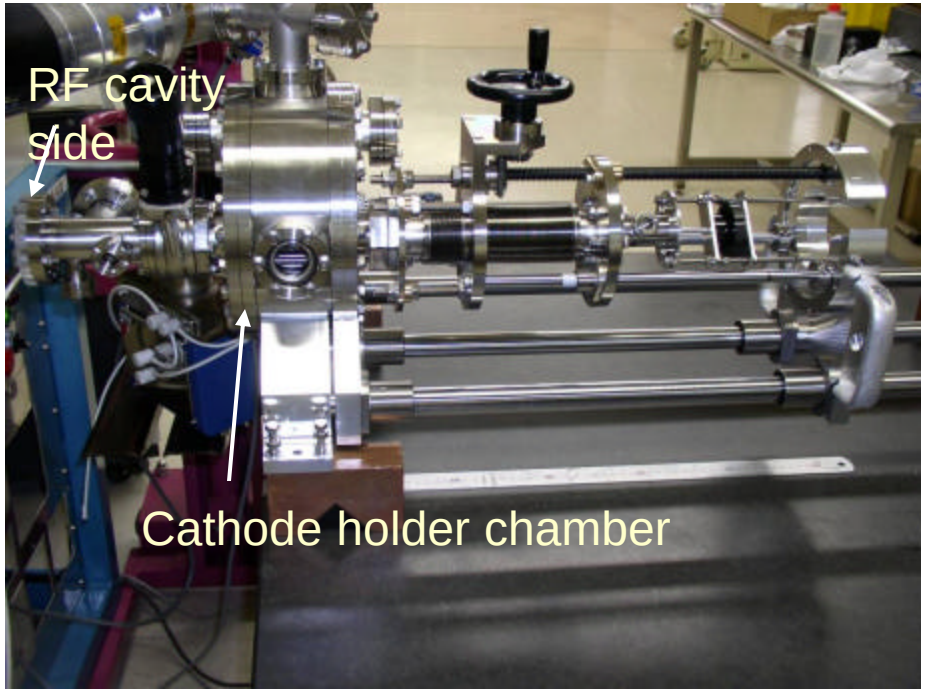
Max. Cathode surface field:
190 MV/m

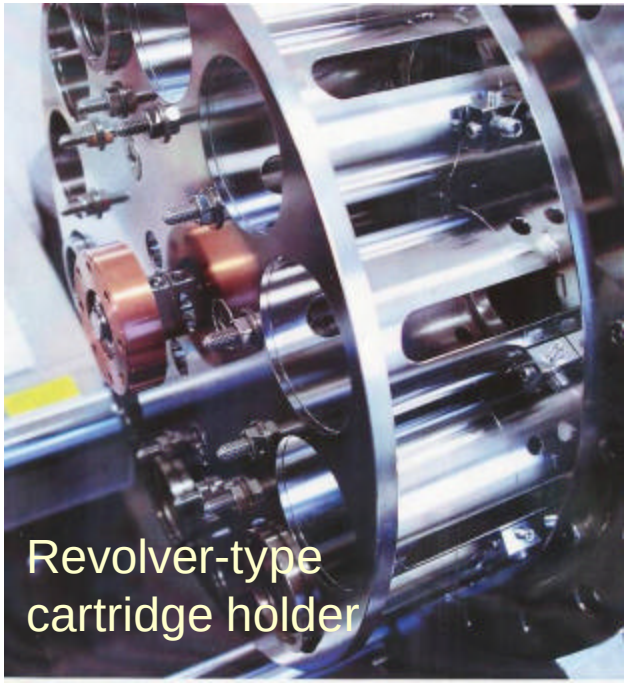
Max. surface field:
210 MV/m

With this high field:
Laser incidence makes no rf-breakdown!

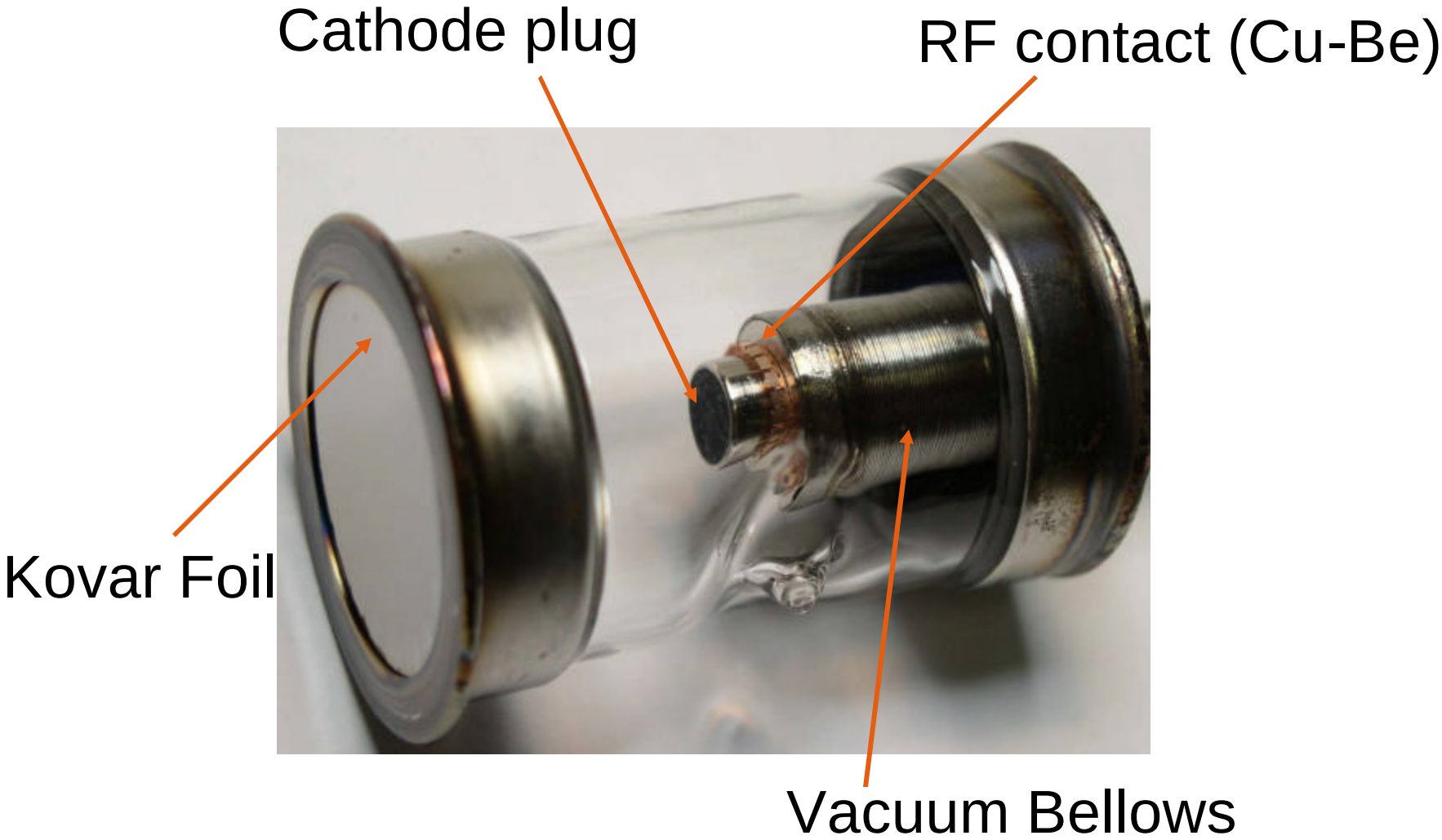
4.6 Surface Diagnosis with Cartridge-type Cathode System

- New cartridge holder accommodates up to 12 cartridges
- Development of transparent-type Diamond photocathode
- Easy to apply other kinds of photocathode
  - Ideal study for cathode surface physics
  - Rf Breakdown study





Cartridge-type Cathode

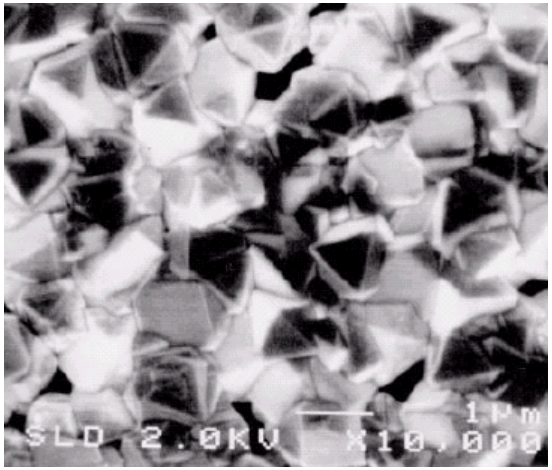


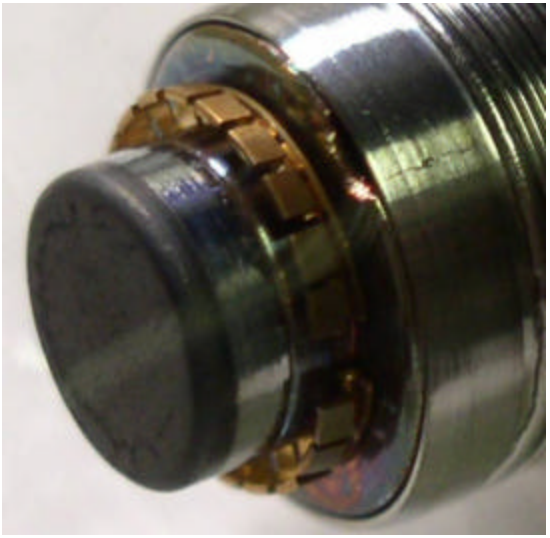
4.7 Diamond Photocathode

Characteristics of Diamond Photocathode

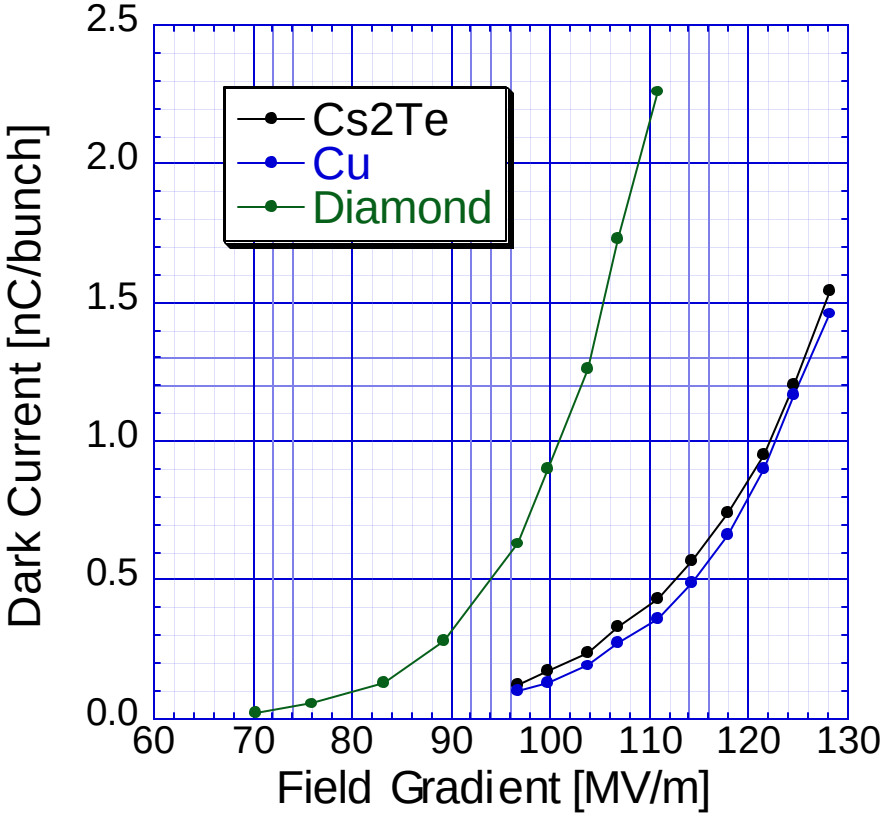
- Highest QE among all photocathodes
  (70%@125nm, however just 197nm-FHG available.)
- Wide band-gap semiconductor (Eg=5.5eV)
- NEA photocathode
- Surface is chemically stable
  (no need of UHV)

Diamond Photocathode

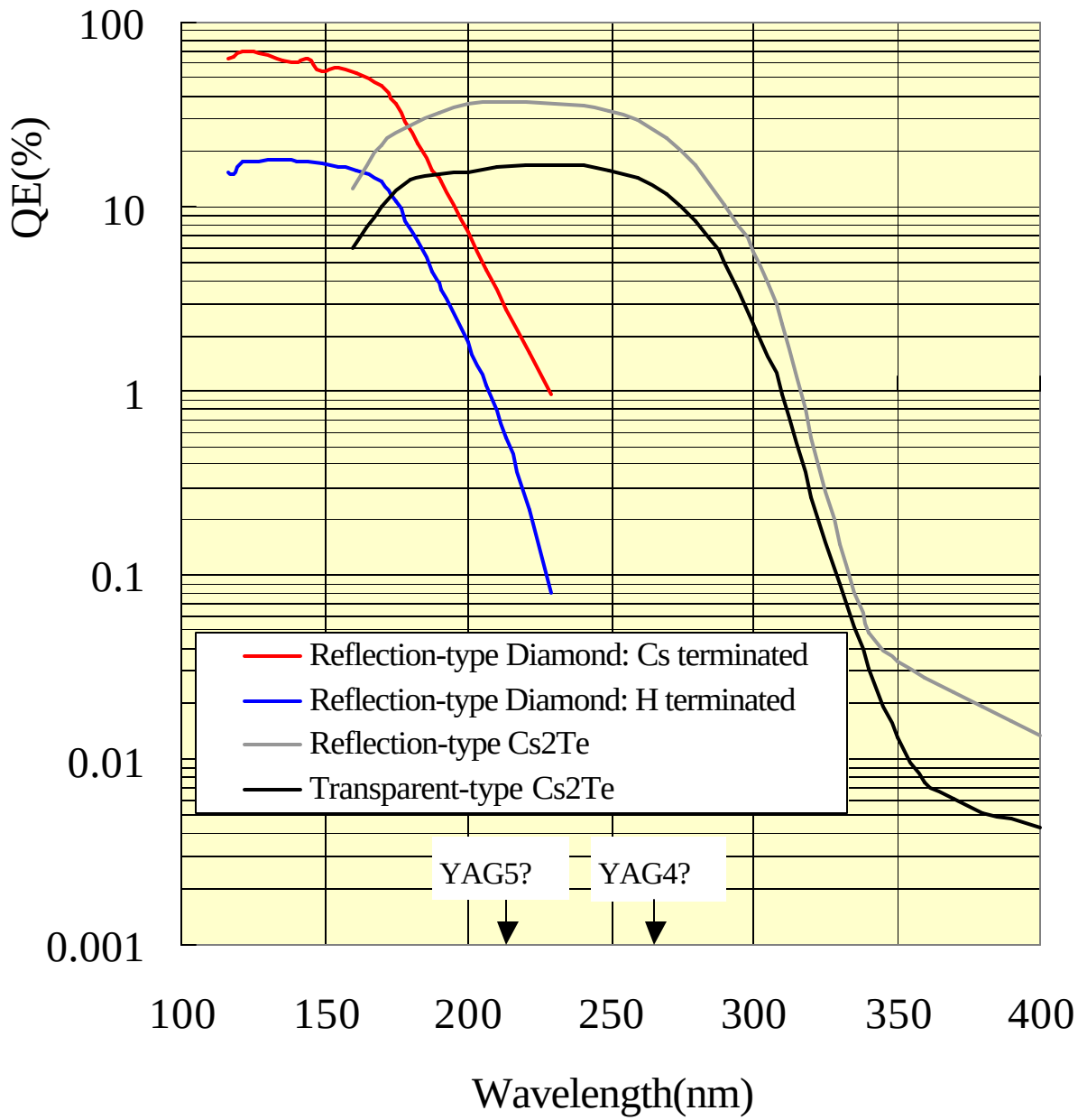


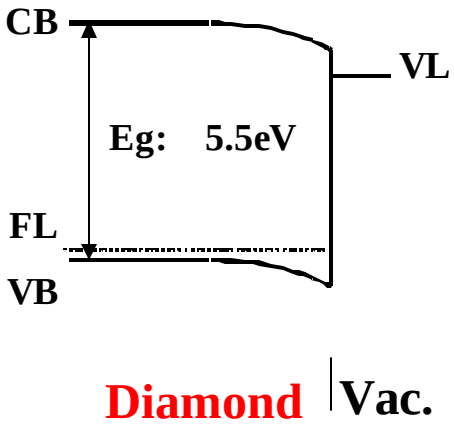


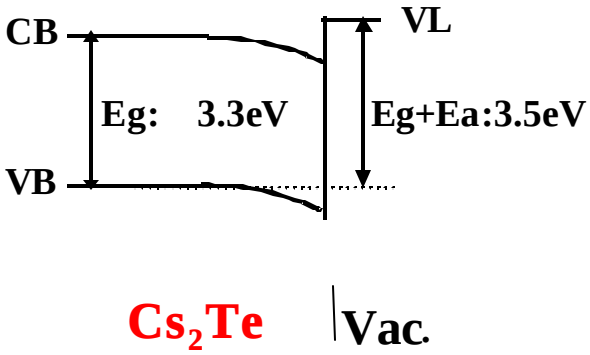
Dark Current of Diamond Photocathode



4.5 High QE Photocathode







Summary

- Our purpose is generating the lowest emittance electron beam with long-term stability.
- Low Emittance Beam can be generated and evaluated with
  - Long-term laser stability: 0.7~1.3% (rms) for 1 Month
  - 3D-laser profile: Spatially Flattop & Rectangular Pulse
  - High Gradient Field: 190 MV/m @ Cathode
  - High Resolution Emittance Monitor: Resolution<1 πmm•mrad
- Cartridge-type Cathode System makes easy to study cathode surface physics & RF Breakdown.
- Transparent cathode for fiber bundle shaping system might have a lot of possibilities, but currently have discharge problems.