REVIEW OF ADVANCED LASER TECHNOLOGIES FOR PHOTOCATHODE HIGH-BRIGHTNESS GUNS

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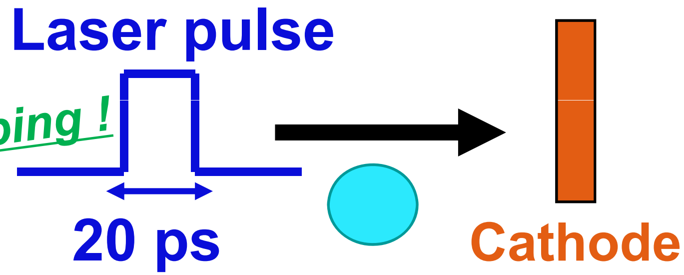
JASRI/SPring-8

Background: **The next generation X-ray light sources (X-FEL, ERL) require electron beams with very low emittance (high brightness source).**

Key Technology :3D-Laser pulse shaping !



Photocathode**: One of the most reliable candidates for this high-brightness electron source is a photocathode gun.**

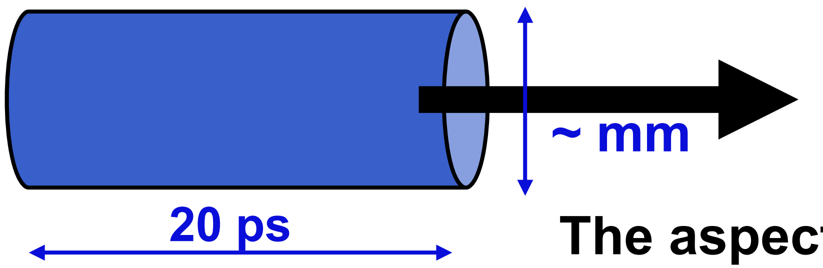
Physical background of ideal laser profile

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

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



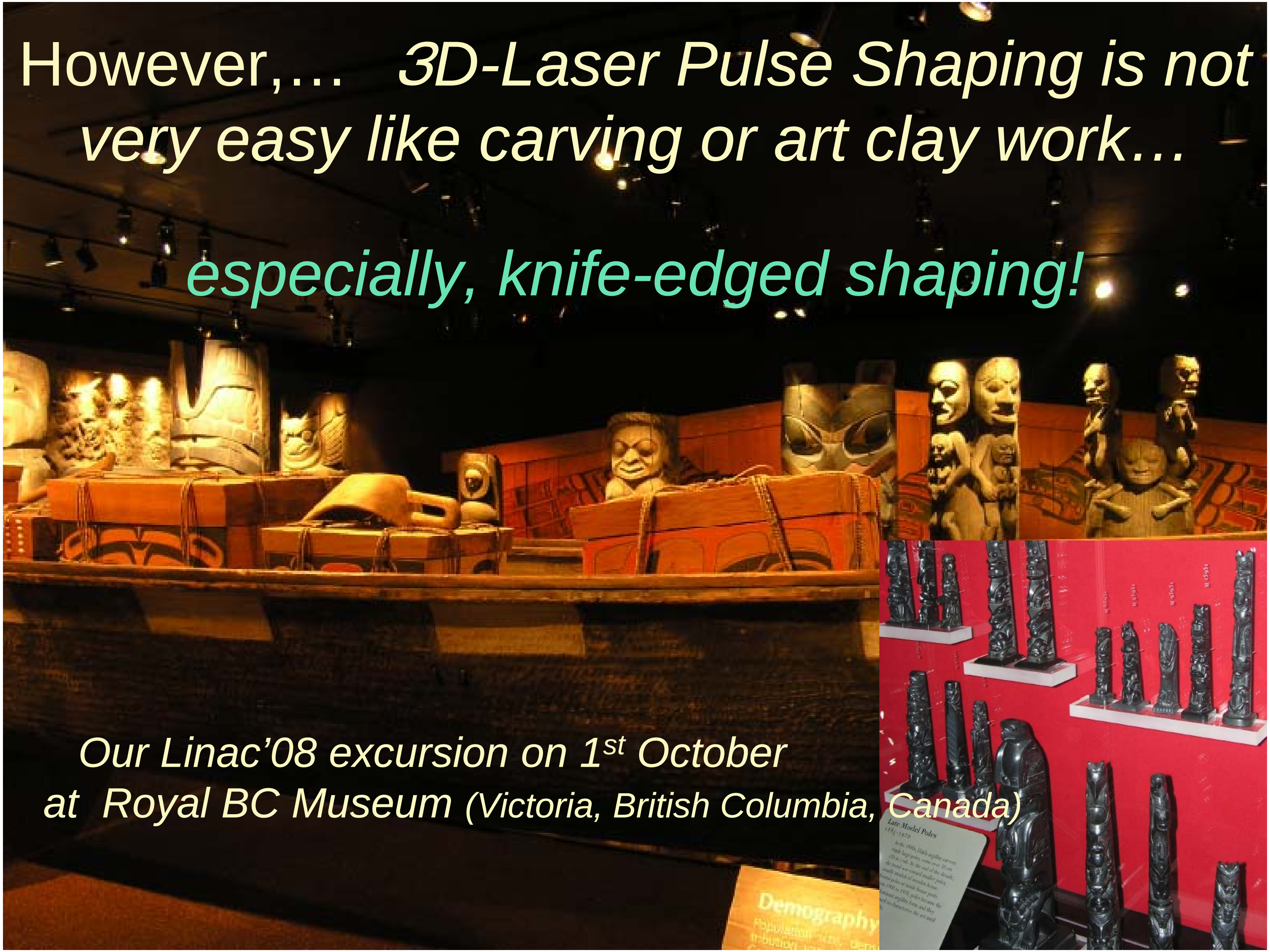
Note that, in real case ideal 3D-shape can be different!

The aspect ratio of the Laser Profile is important!

However,… *3D-Laser Pulse Shaping is not very easy like carving or art clay work…*

especially, knife-edged shaping!

Our Linac'08 excursion on 1st October
at Royal BC Museum (Victoria, British Columbia, Canada)



Optimization of laser profiles and schemes

~ Spatial & Temporal ~

History of Ideal Beam Shape Evolution

our contributions for following requirements

"Beer can"

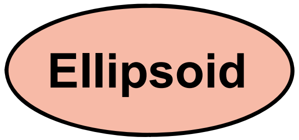
Spatial Shaping

Deformable Mirror (Wave Front Control, also!)

Pulse (Temporal) Shaping

SLM (Spatial Light Modulator)

UV- Pulse Stacker (birefringence α-BBO)



K-V distribution

3D-pulse shaping (uniformly filled ellipsoidal)

Linear space charge fields in each direction (Lorenz invariant).

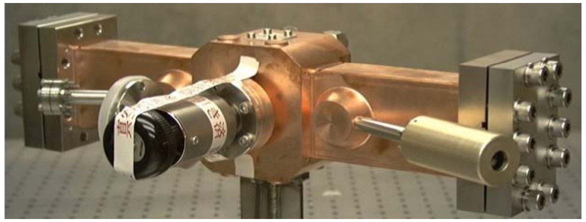
Fiber Bundle with backward illumination

Luiten scheme (2004)

Start from femtosecond pulse

Z-polarization with Schottky effect

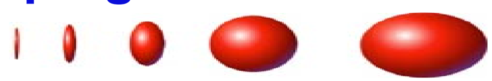
History of SPring-8 Photocathode RF Gun



1996 Study of photocathode RF guns started.
1999 First beam test with YLF laser system
2001 New Ti:Sapphire laser system installed.
All concepts of 3D-Laser shaping technologies were proposed.
2002 Emittance 2.3 πmm mrad @0.1 nC (pulse width: 5 ps) with homogenizing in Spatial profile (using Microlens array)
Cartridge type cathode (transparent) development started.
2003 New gun & laser test room (fully environmental control) constructed and an accelerating structure installed.
Fiber Bundle shaping for cathode backward illumination was demonstrated.

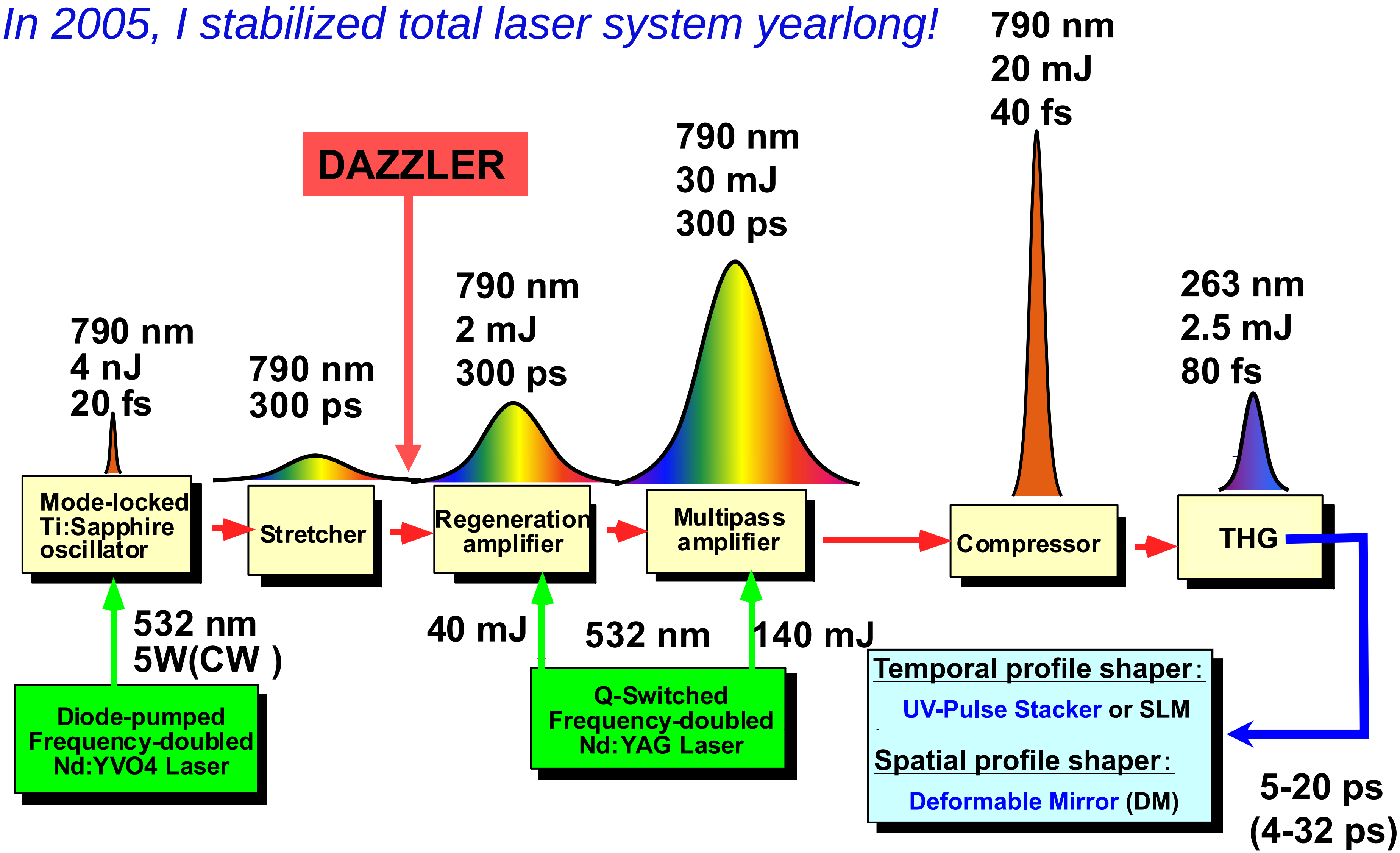
2004 Maximum field of 190 MV/m at cathode
Laser was stabilized with 0.2%(rms @0.3TW fundamental), 1.4%(rms @THG; 263 nm), for 1.5 Month.

2005 3D-laser shaping system was completed (10 month continuously operated).
2006 Emittance 1.4 πmm mrad @0.4 nC (pulse width: 10 ps) with "Beer can" laser pulse (Flattop SP (DM); Square TP (PS))
2007 Hollow beam incidence system with 3D-laser shaping was developed. Z-pol. gun was proposed (in 2006).

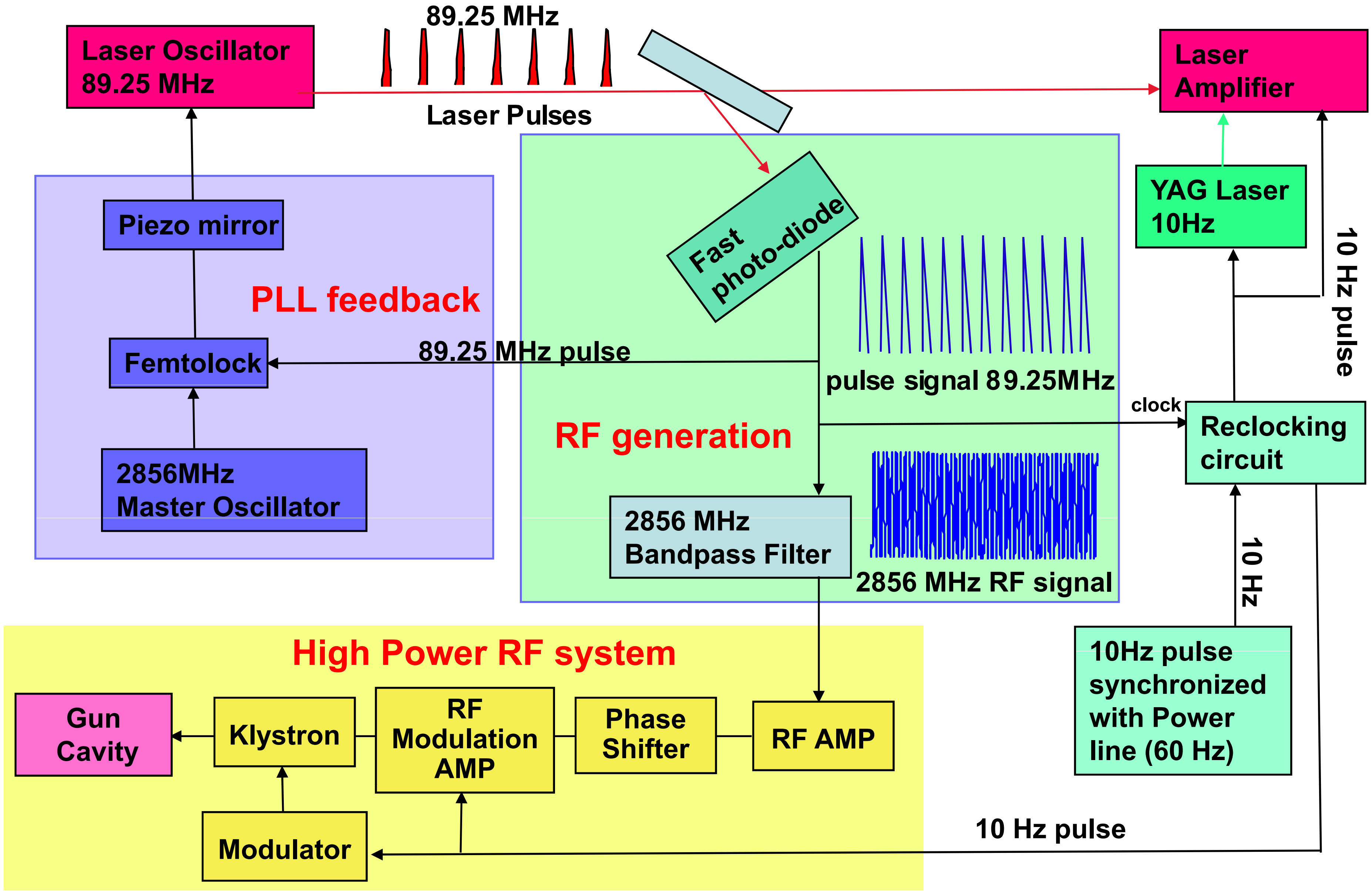


Spring-8 Photocathode Laser System Configuration

In 2005, I stabilized total laser system yearlong!



Laser & RF Synchronization



Comparison of synchronization techniques

Laser generation with master RF	RF generation from Laser pulse
Synchronization is limited by the motion speed of piezo device.	Synchronization is not limited by the motion speed of piezo device.
RF stability depends on master RF source	RF stability depends on Laser oscillator

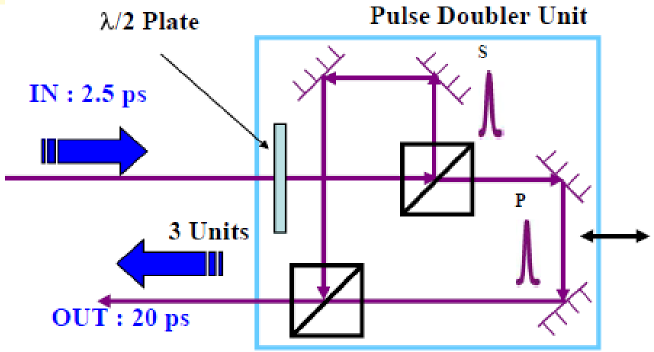
" Beer can" UV-laser pulse shaping system

UV- Laser source (yearlong stability!)

Laser Pulse Energy : 1.4% @THG

Timing Jitter < 0.3 ps

Cylindrical



Spatial Profile:

Distribution: Flattop

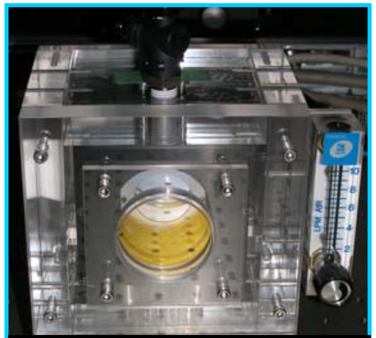
Deformable Mirror

Temporal Profile:

Pulse duration: 4 ~ 32 ps

UV- Pulse Stacker

Gaussian



Deformable Mirror

Pulse duration: 2.5 ps

Pulse duration: 32 ps

Diameter : 1 mm

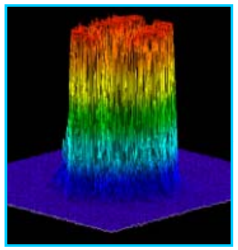
DAZZLER

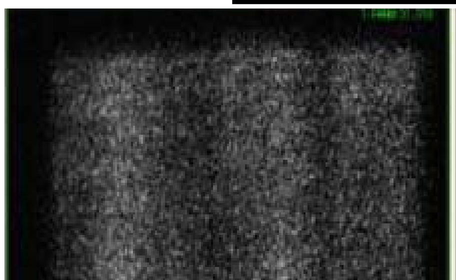
Pulse Stacker

10 pps

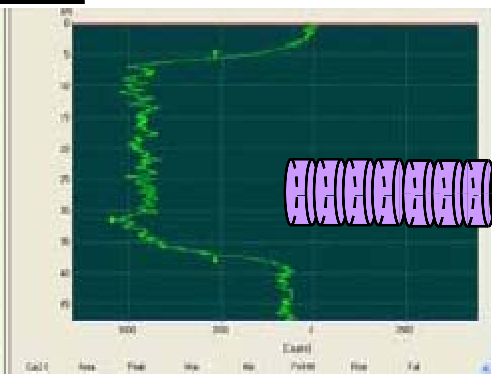
Deformable Mirror

Flattop





Pulse Stacking rods
(4 birefringent crystals)



Present 3D-laser pulse shaping

"Beer can"

DAZZLER:
micro pulse shaping

↓

THG

↓

UV-Pulse Stacker:
macro pulse shaping

↓

Deformable mirror:
transverse shaping

↓

Normal incidence
to the cathode

Spatial shaping with Deformable Mirror

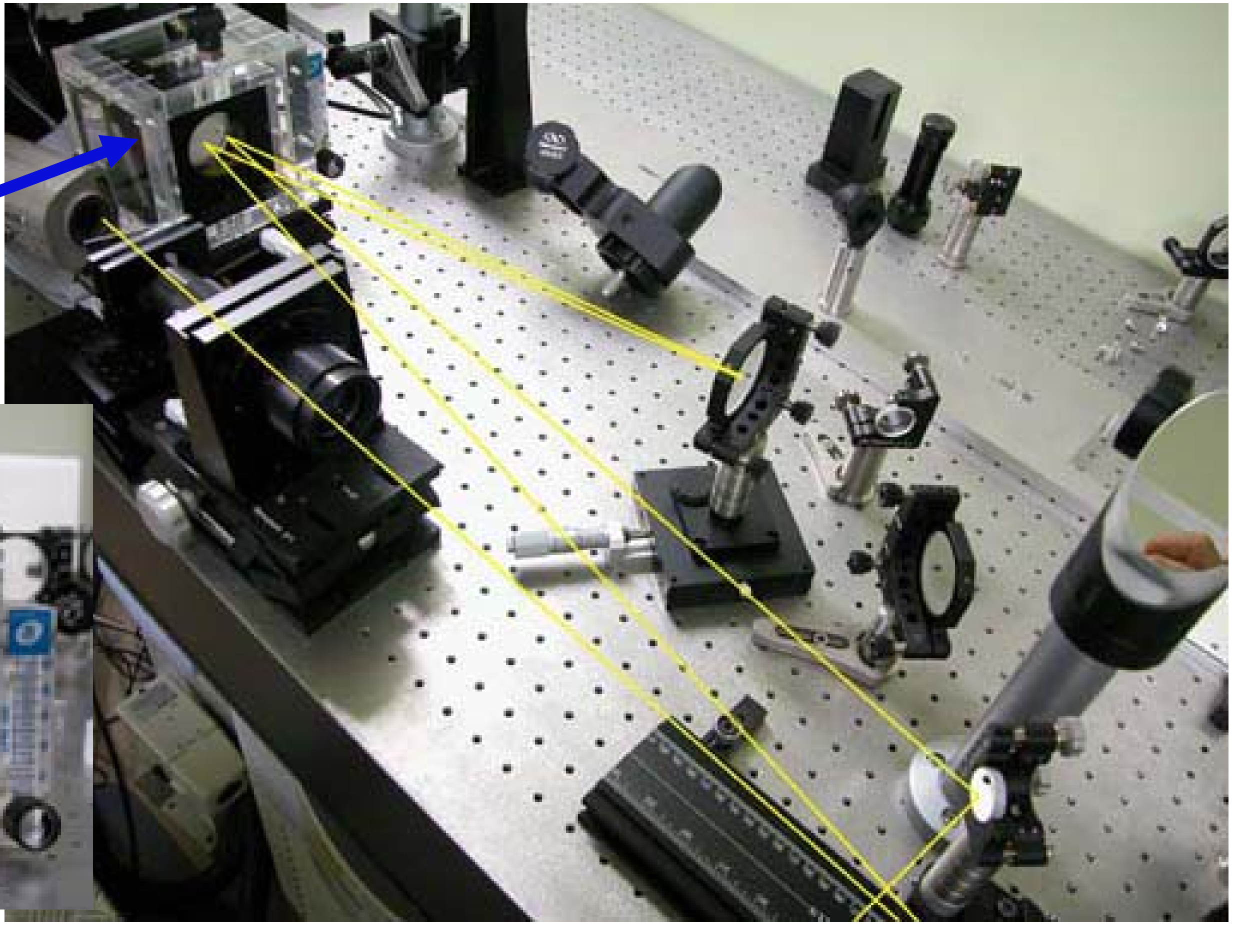
Cylindrical

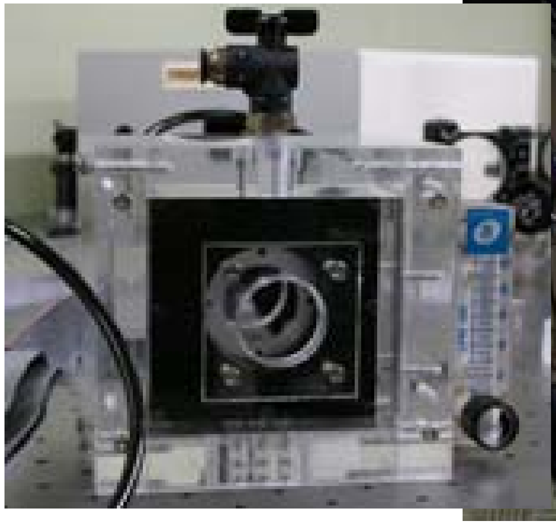
Mirror cell: 59
Deformation step: 250

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

AI-Algorism for spatial shaping is under development

DM
Double reflection

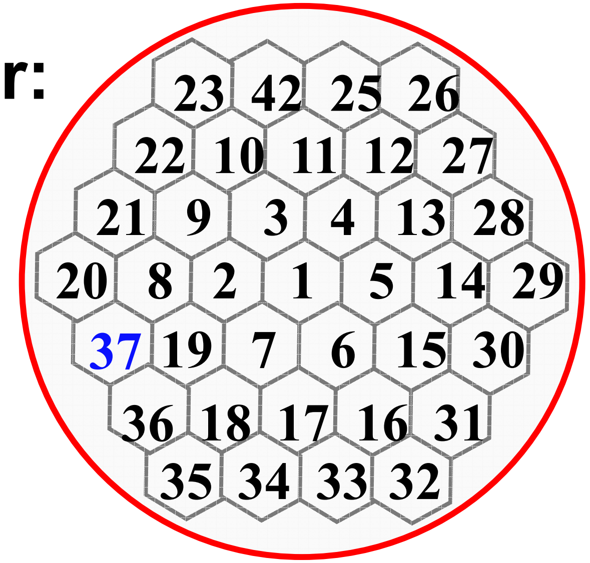


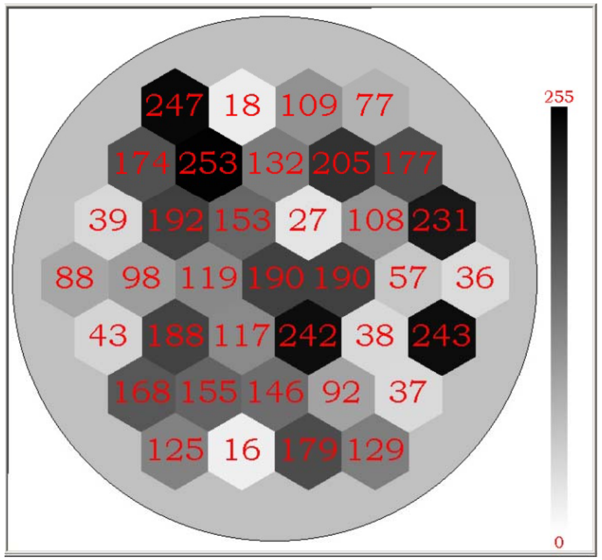


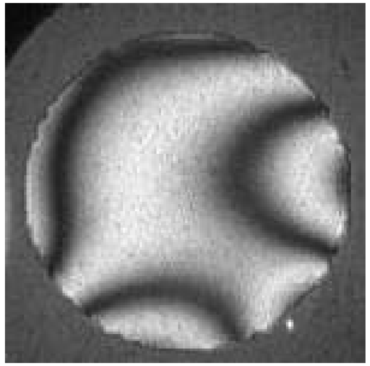
Structure of DM-Actuator:

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

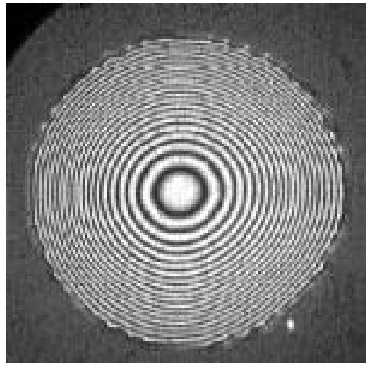
Actuator:



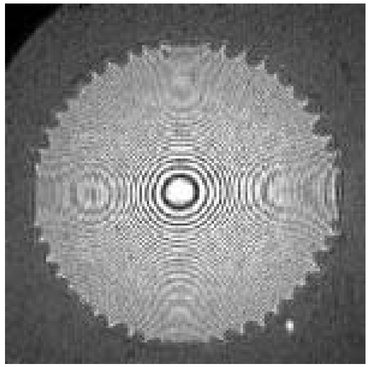




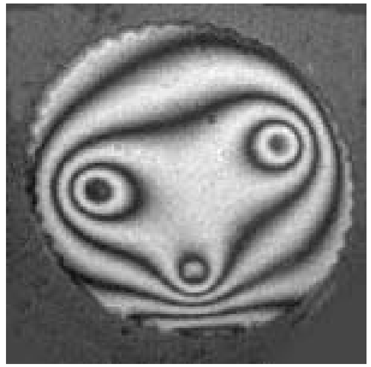
Initial State (All: 0V)



All: 125V



All: 255V (Max. Voltage)



Random Voltage

http://www.okotech.com/

Basic Concept of genetic algorisms

Cylindrical

Genetic Algorithm

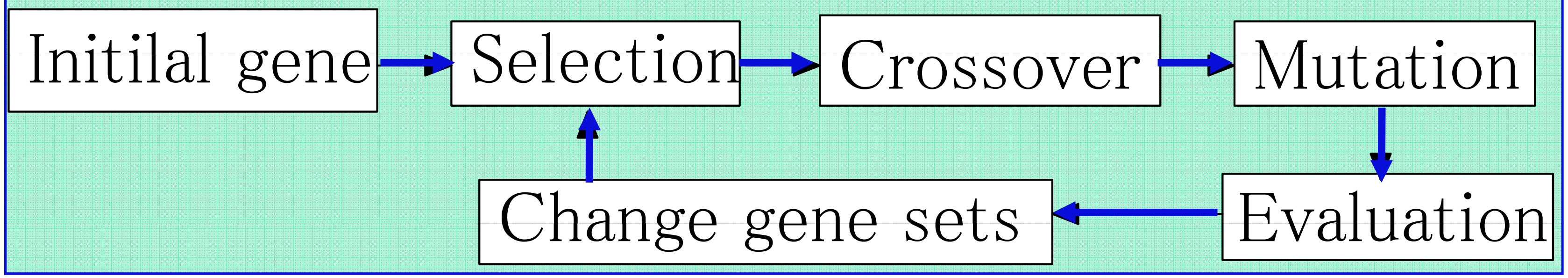
〈Basic Process〉

1) **Coding** : Digitize control parameters

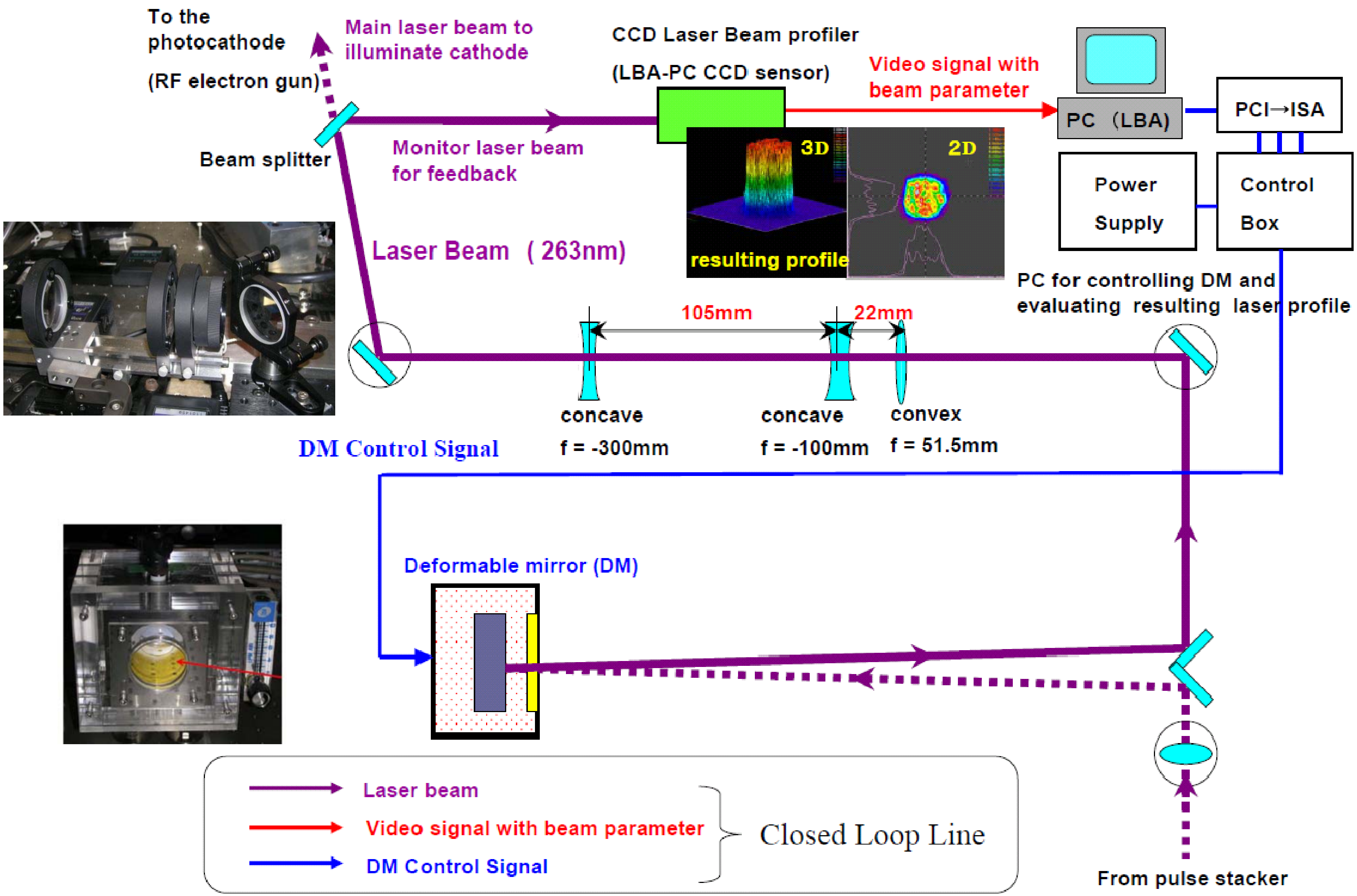
gene	1	0	1	1	1	0	0	0

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

3) Basic Process



Closed Control System for experiment



Weight of each term of fitting function for *Flattop*

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

$$f(\textit{profiles}) = a① + b② + c③ + d④ + e⑤ + f⑥ + g⑦ + h⑧ + i⑨$$

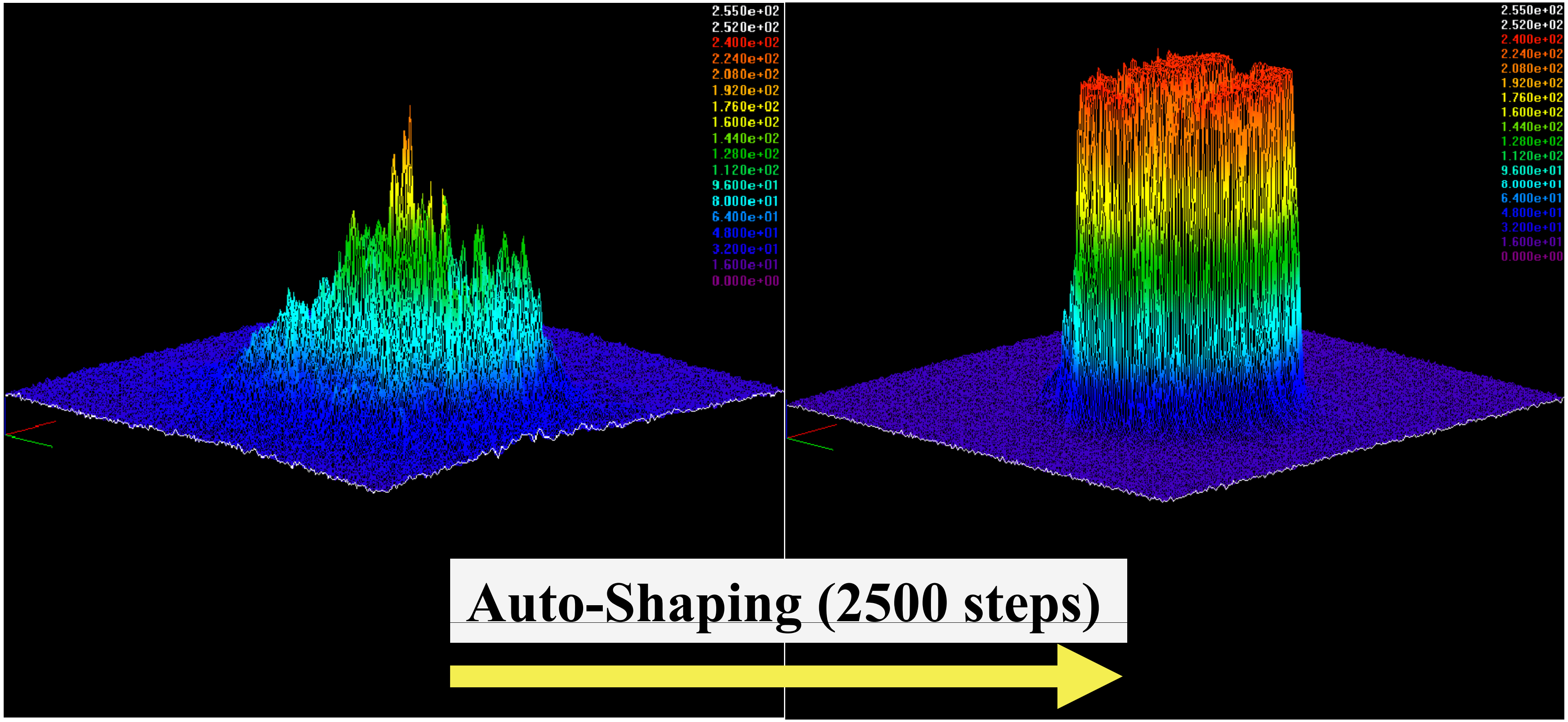
Term		Meaning	Absolute convergence value with 500step	System Weight
1	Top Hat Factor	Maximize the Top Hat Factor (0 - 1) (Flattop: THF = 1.0)	0.5	120
2	Effective Diameter	Minimize the difference from the diameter of set circle	25	2.4
3	Flatness (SD/mean)	Minimize the standard deviation divided by the 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

Results of spatial shaping with DM

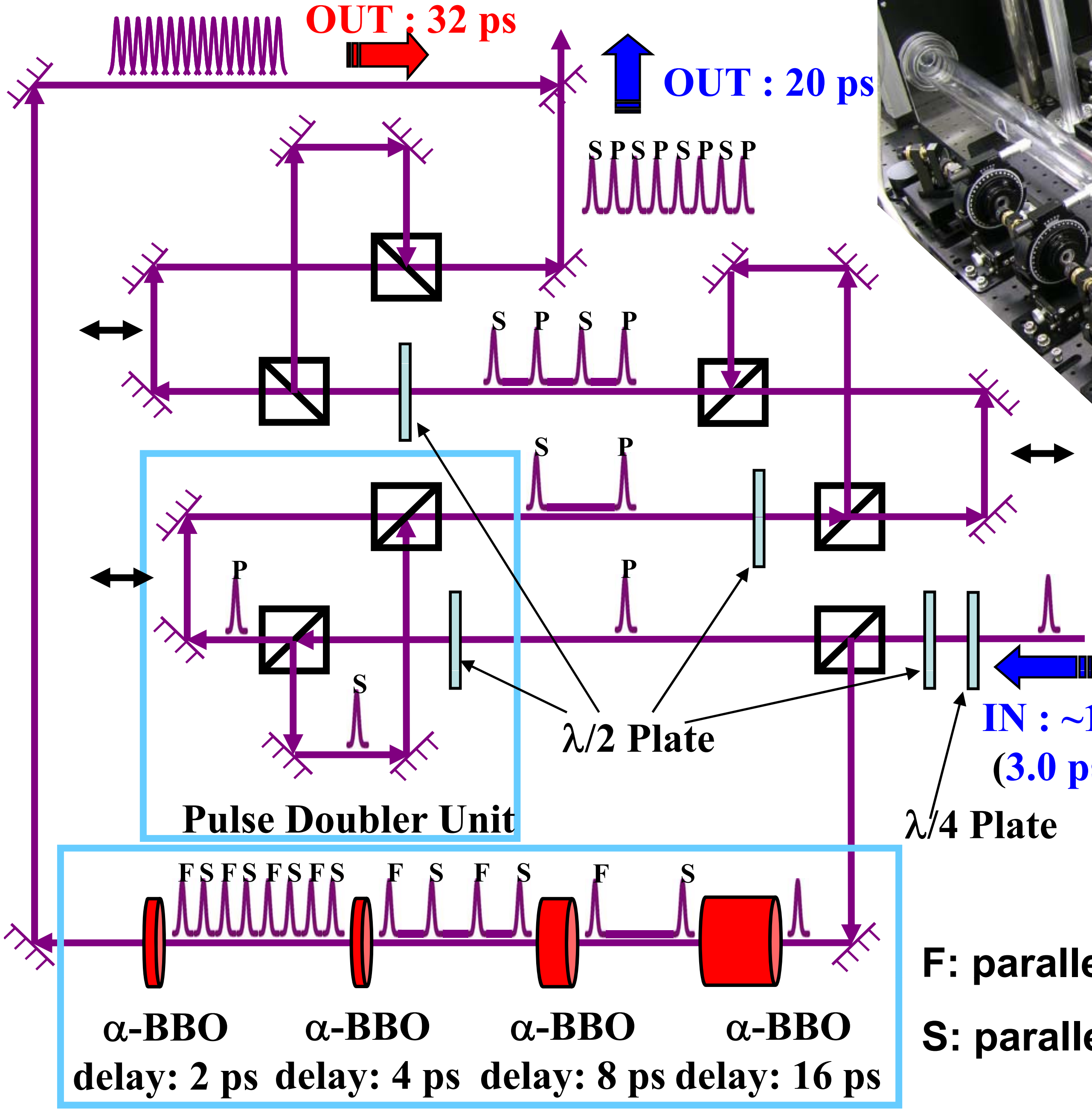
Cylindrical

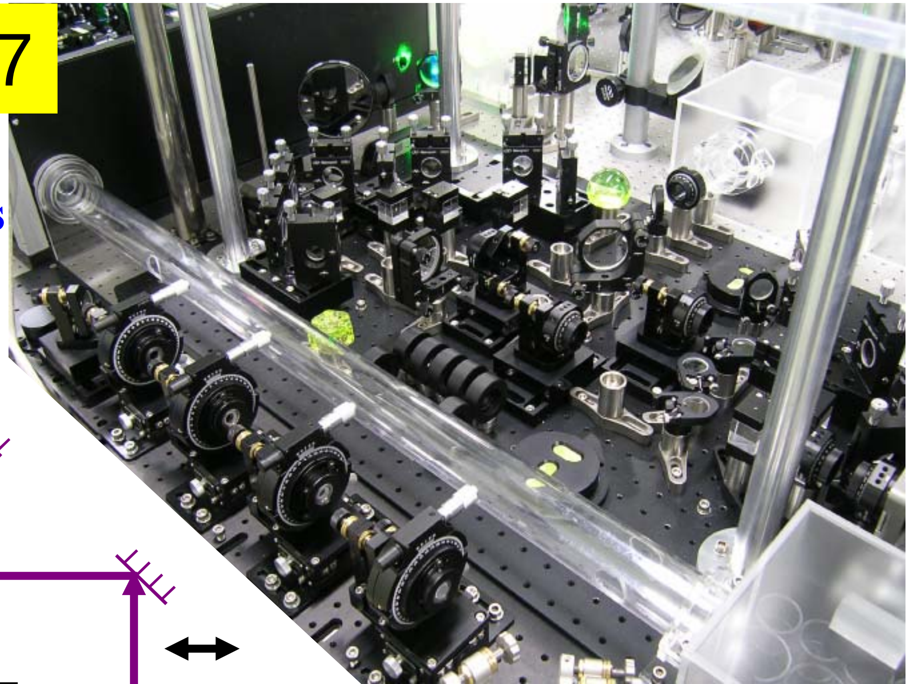
- Computer-aided DM for UV (THG)

→ **Flattop shaping OK!**



Pulse Stacking System in 2007

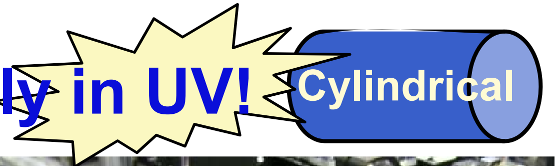


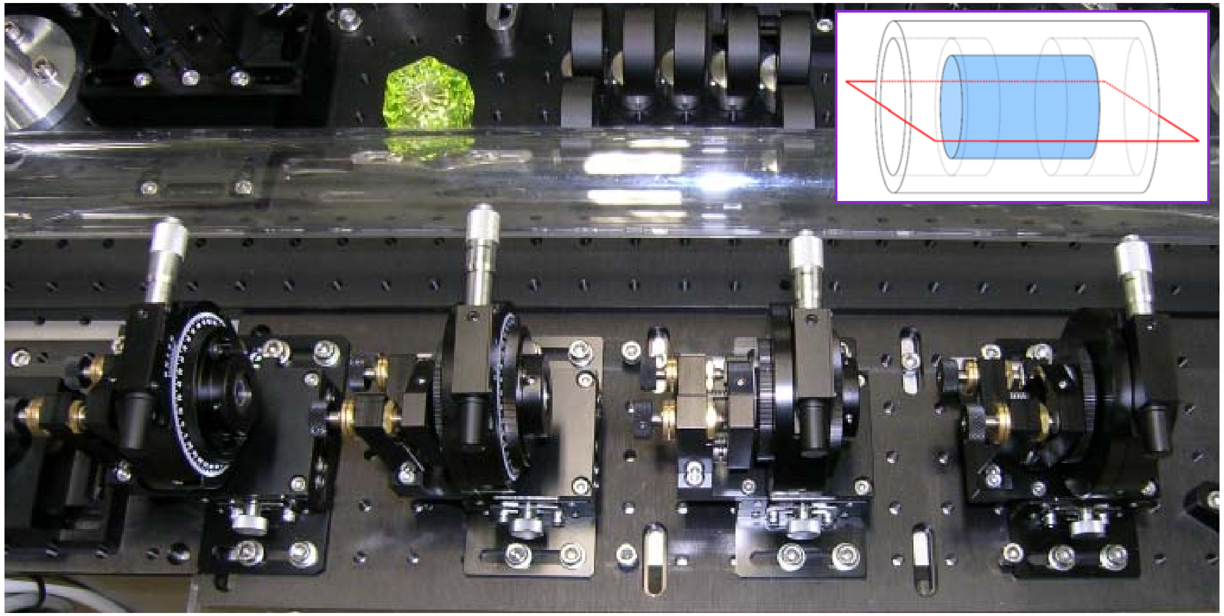


F: parallel to fast-axis of crystal

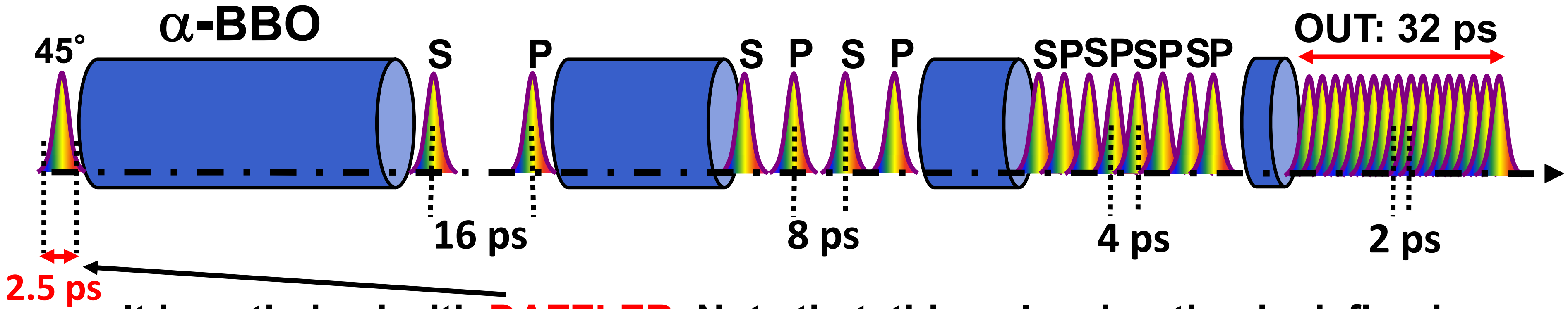
S: parallel to slow-axis of crystal

Pulse Stacking Rods ~ shaped directly in UV!

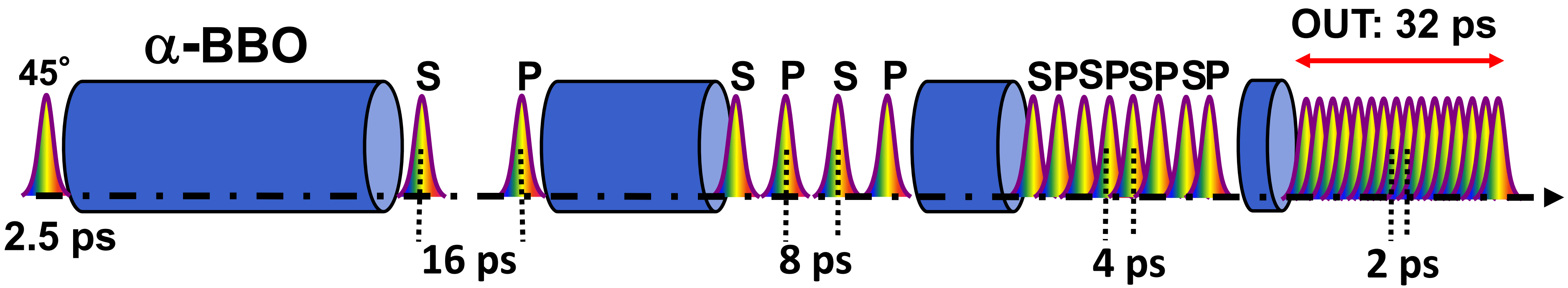




UV- chirped pulse stacking birefringent crystal rods

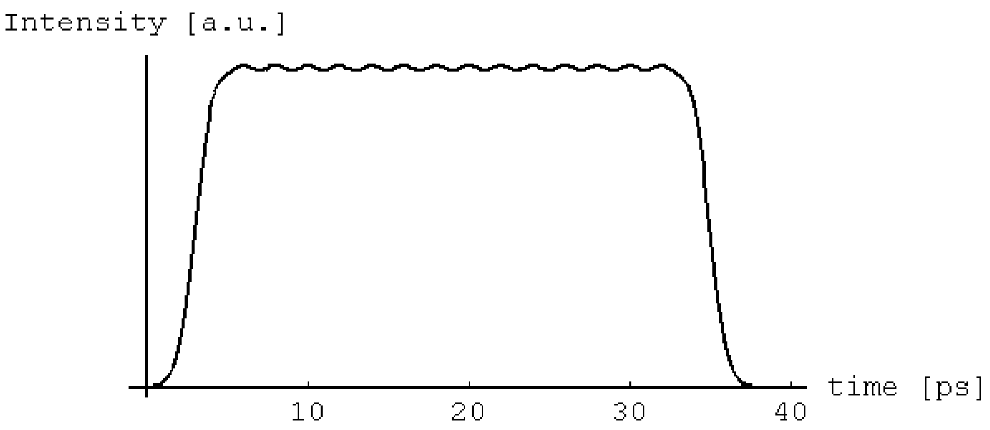


It is optimized with DAZZLER. Note that, this pulse duration is defined at the cathode as a stretched pulse due to the dispersion through the transparent optics in laser transport (GDD of BBO @ 263nm).

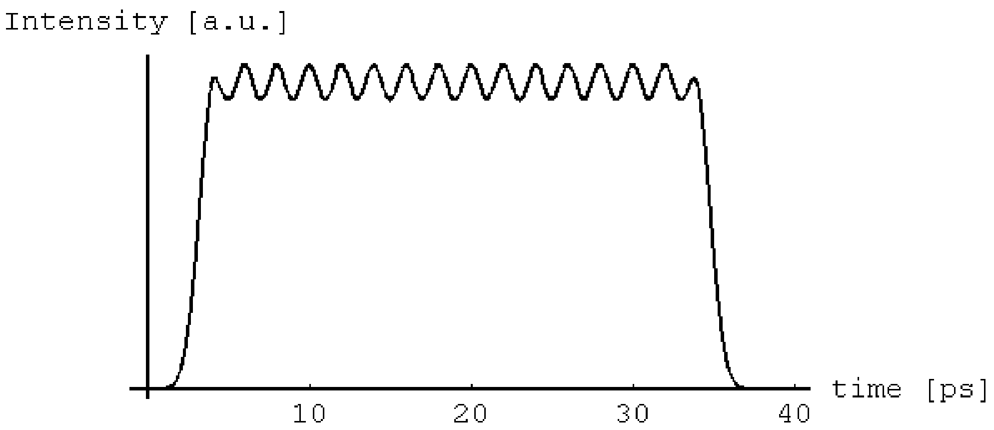


Results of Mathematica:

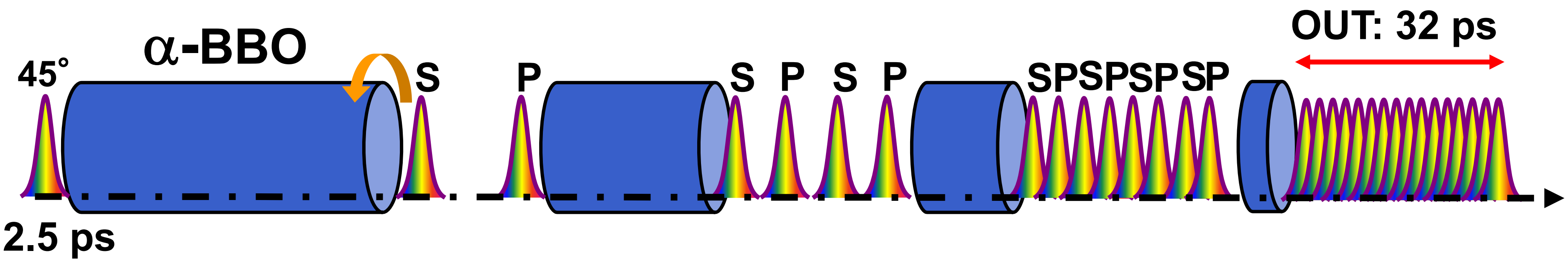
dt1=16ps, dt2=8ps, dt3=4ps, dt4=2ps



Input Pulse duration: 2.5 ps

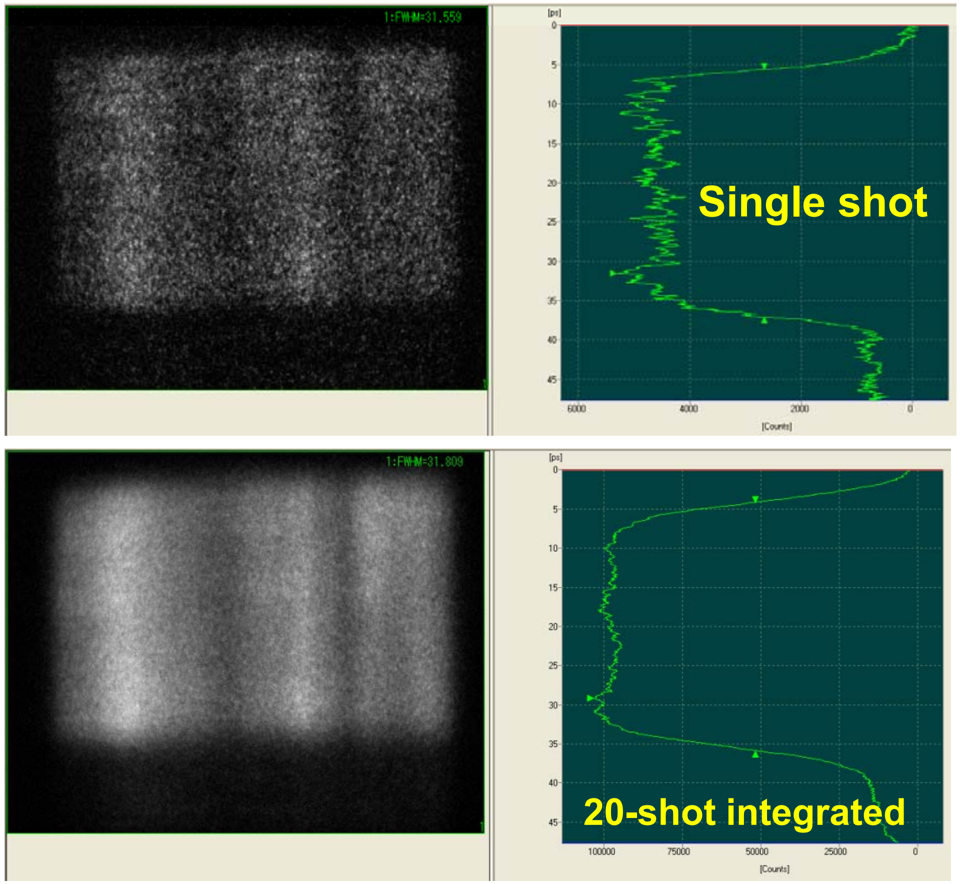


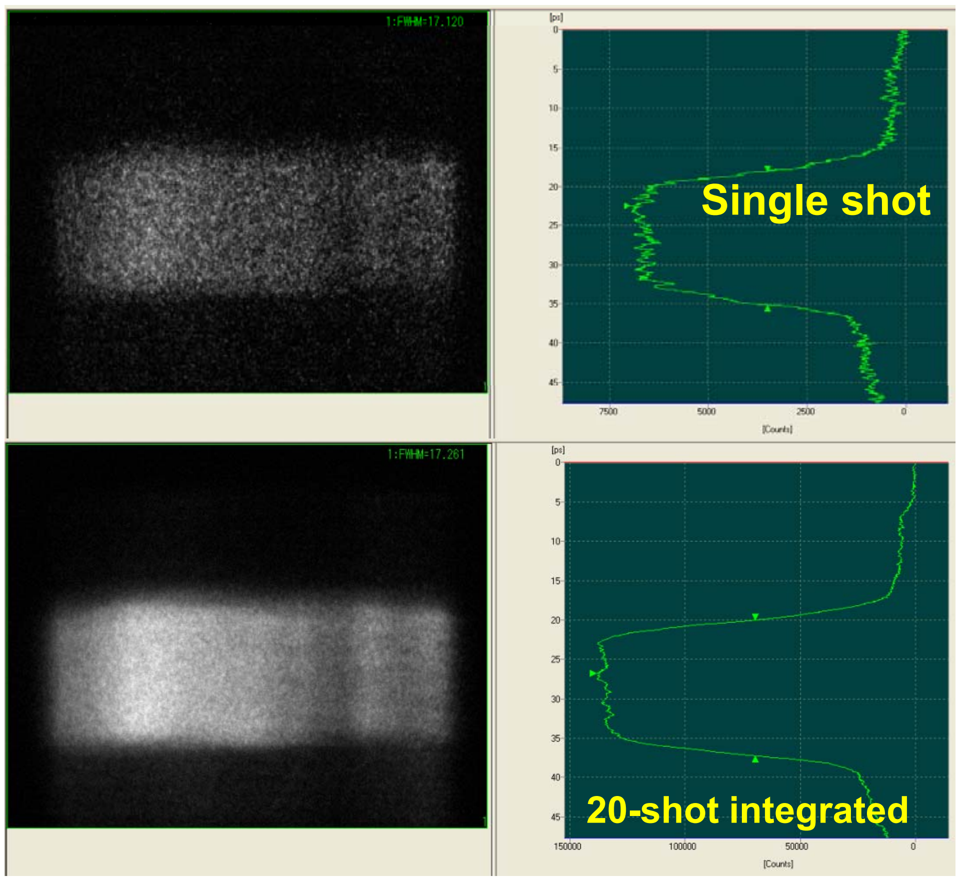
Input Pulse duration: 2.0 ps



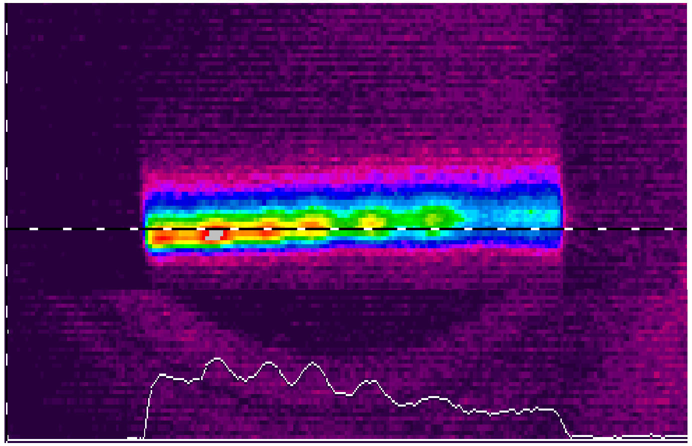
32-ps Square Pulse: ***16 pulse stacking***

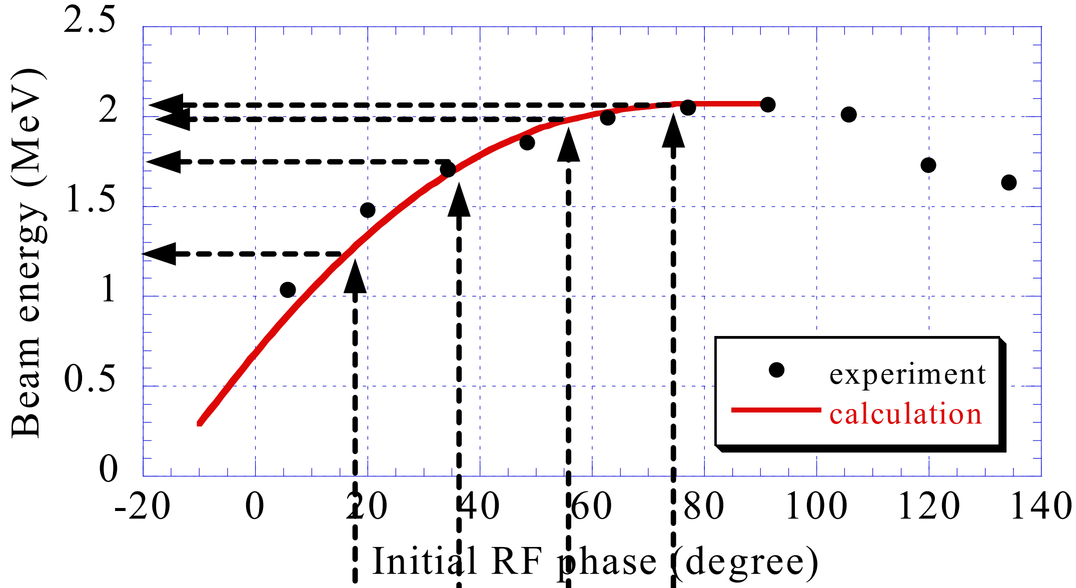
16-ps Square Pulse: ***8 pulse stacking***



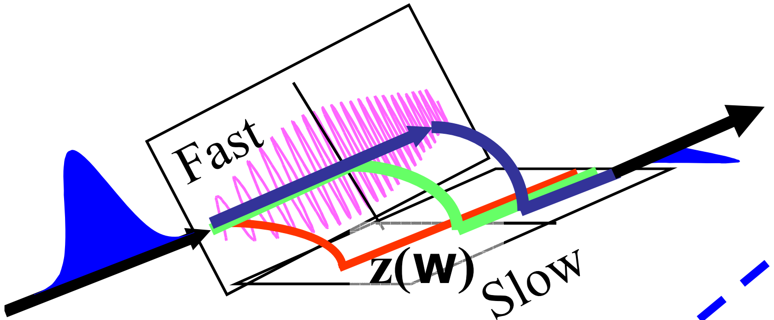


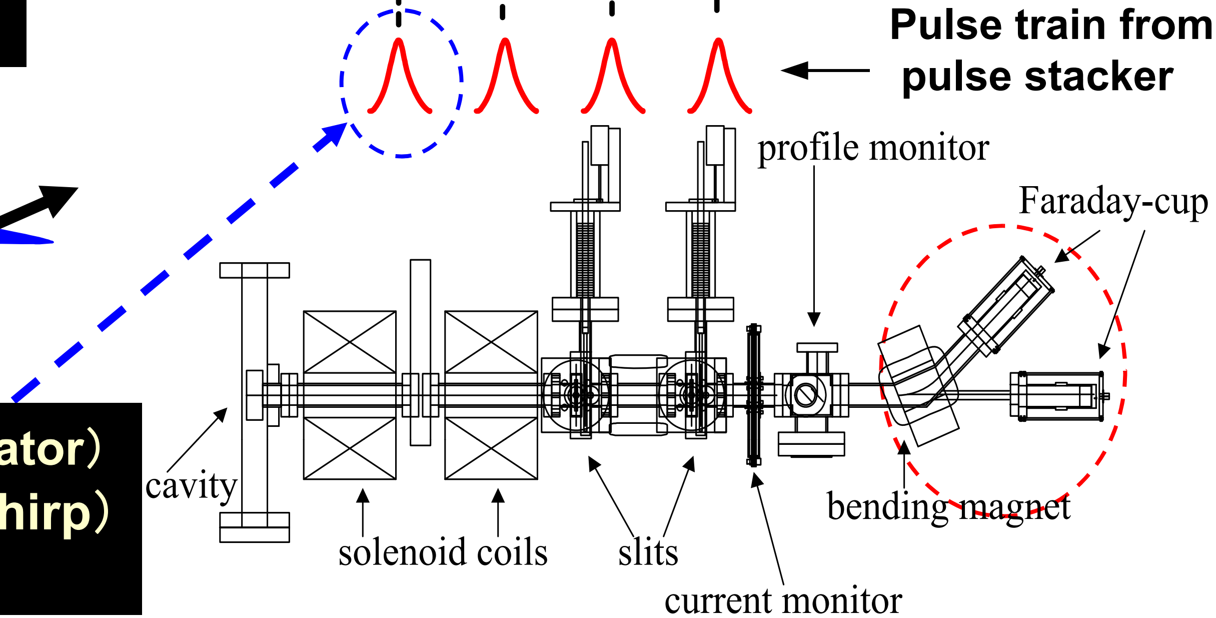
How can we optimize macro & micro pulse with pulse stacking?





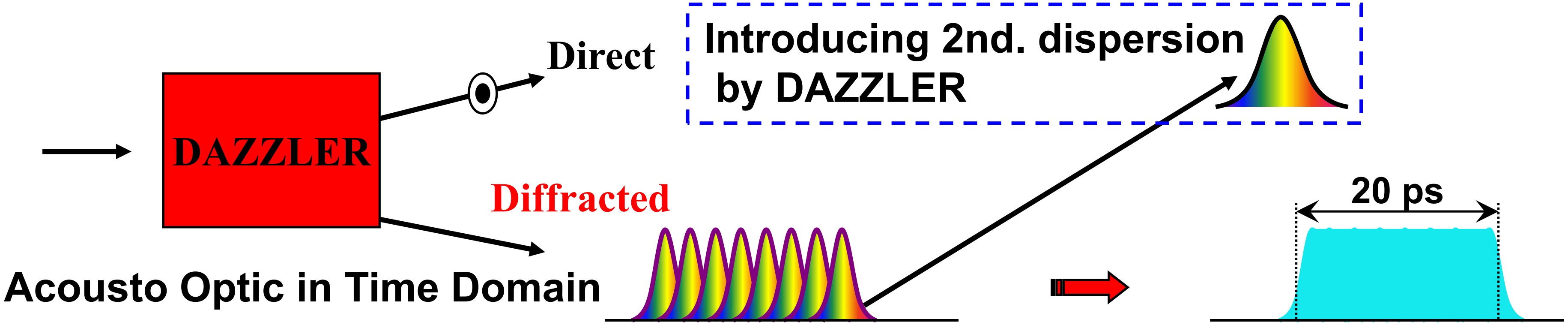
In pulse stacking rods, interval of micro pulses are equivalently fixed.

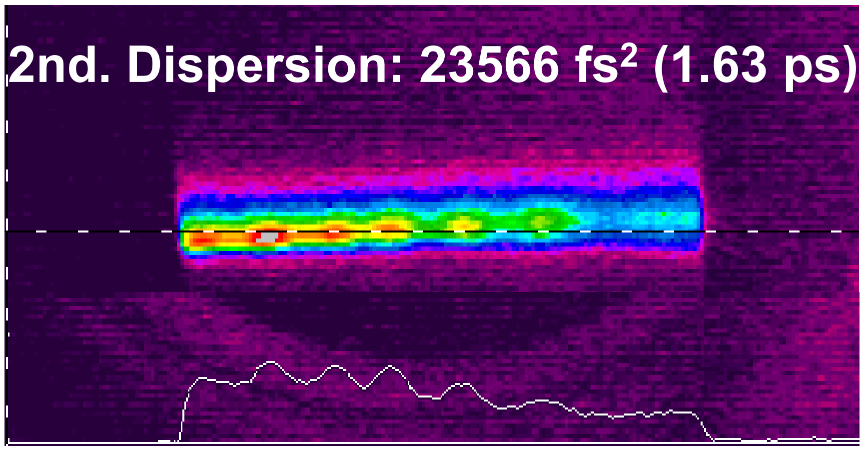


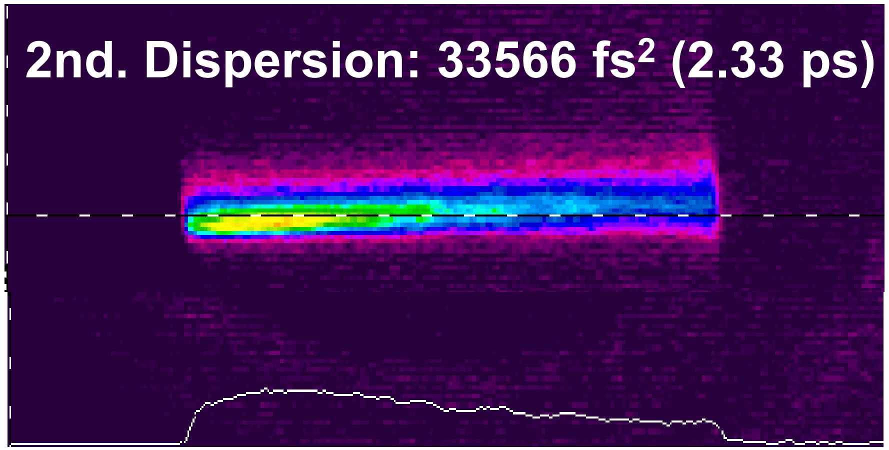


With DAZZLER (AO-modulator) Pulse duration &shape (chirp) are optimized.

Results: Chirped Pulse Stacker＋DAZZLER







Input micro pulse is too short!	***Micro pulse width are optimized!***

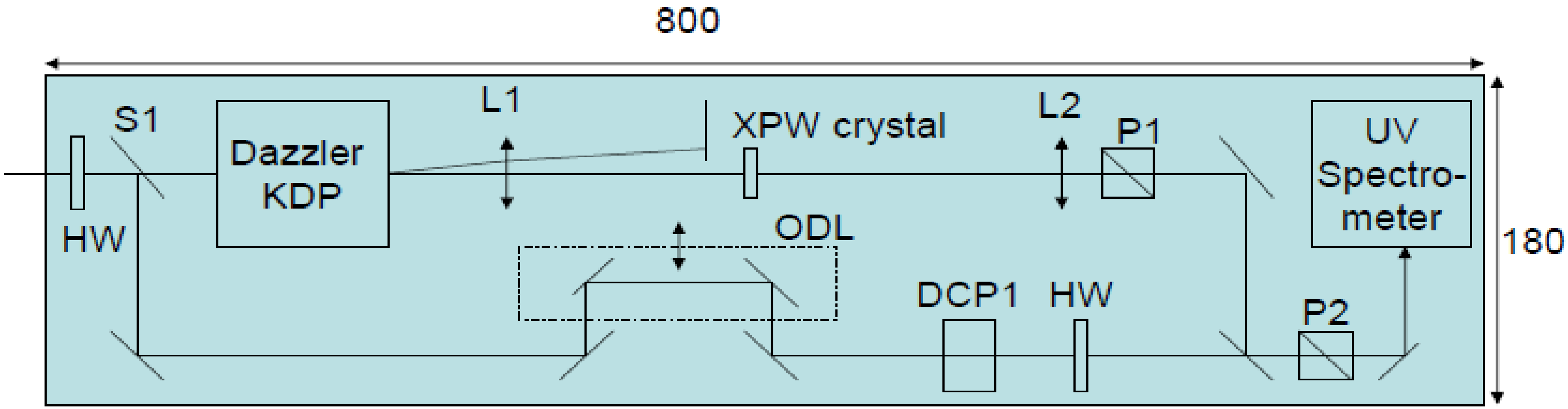
Stacked Pulse Duration: 20 ps

(Input pulse width @ cathode: 3.0 ps)

Our future plan for UV-stacked pulse measurement:

Feedback to DAZZLER in Regenerative Amp.

Spectral Interferometry with UV-DAZZLER



Courtesy of FASTLITE

S1: beamsplitter plate

L1, L2 : lens to focus into XPW crystal

XPW crystal : LiF

P1, P2 : polarizers

DCP1: dispersion compensation plate

HW: halfwave plate

ODL: Optical delay Line

Dimensions in mm

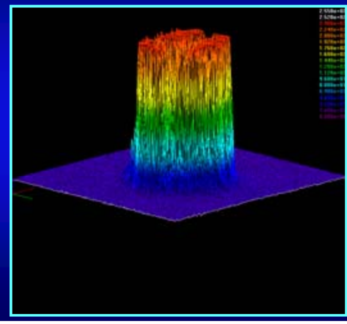
SPring-8 Photocathode Laser source status

A. We realized yearlong stable laser system

Oscillator : 24 hours, 10 months, non-stop
TW- Amp. : 24 hours, 5 months, non-stop
THG: 1.4% rms stability

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

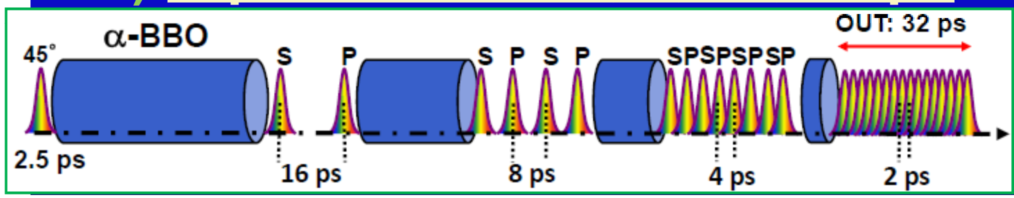
~ However, Laser profiler is damaging for yearlong continuous operation. (Uranium Glass + Camera)

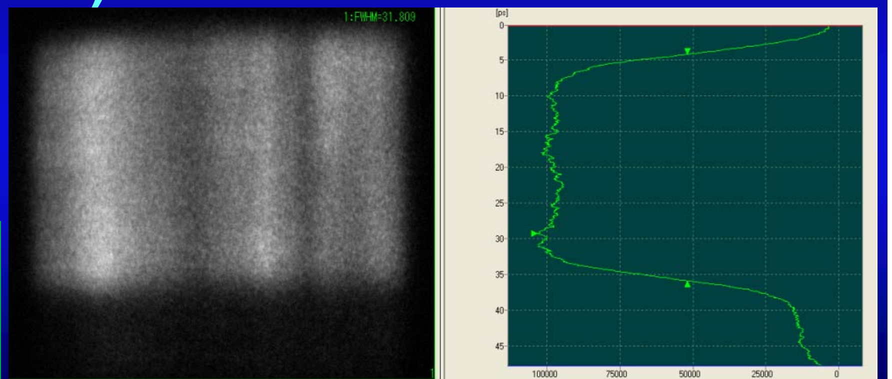


C. Square pulse generation with UV-pulse stacker (rods) was successful at THG (263 nm) !

1) <u>Square Pulse: 5, 10, 20 ps</u>

2) <u>Square Pulse: 4, 8, 16, 32 ps</u>





Emittance measurements
low emittance electron beam generation

~ we are testing with different 3D-parameter ~

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

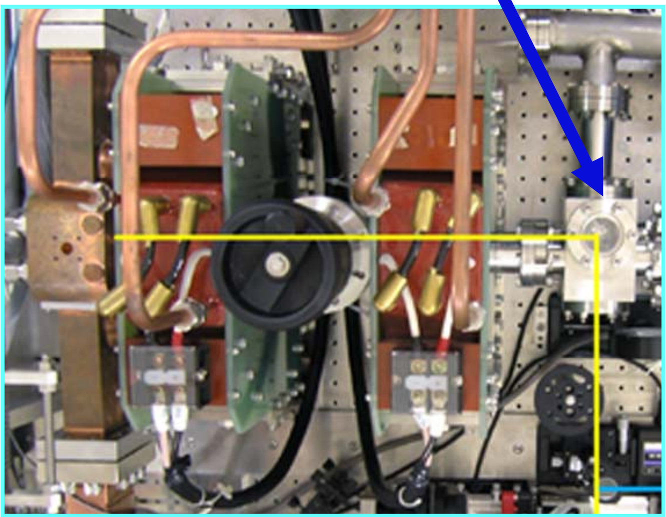
Pulse duration : 20 ps

1.8π mm mrad @ 0.5 nC; 15 ps

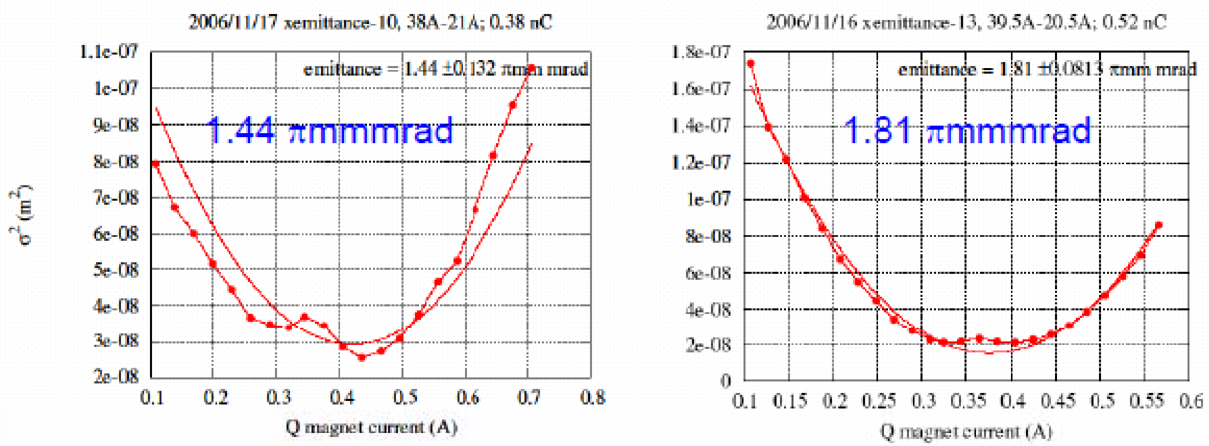
1.4π mm mrad @ 0.4 nC; 10 ps

Y-emittance is always 1.5 times larger!

Normal incident mirror ?



Q-scan fitting

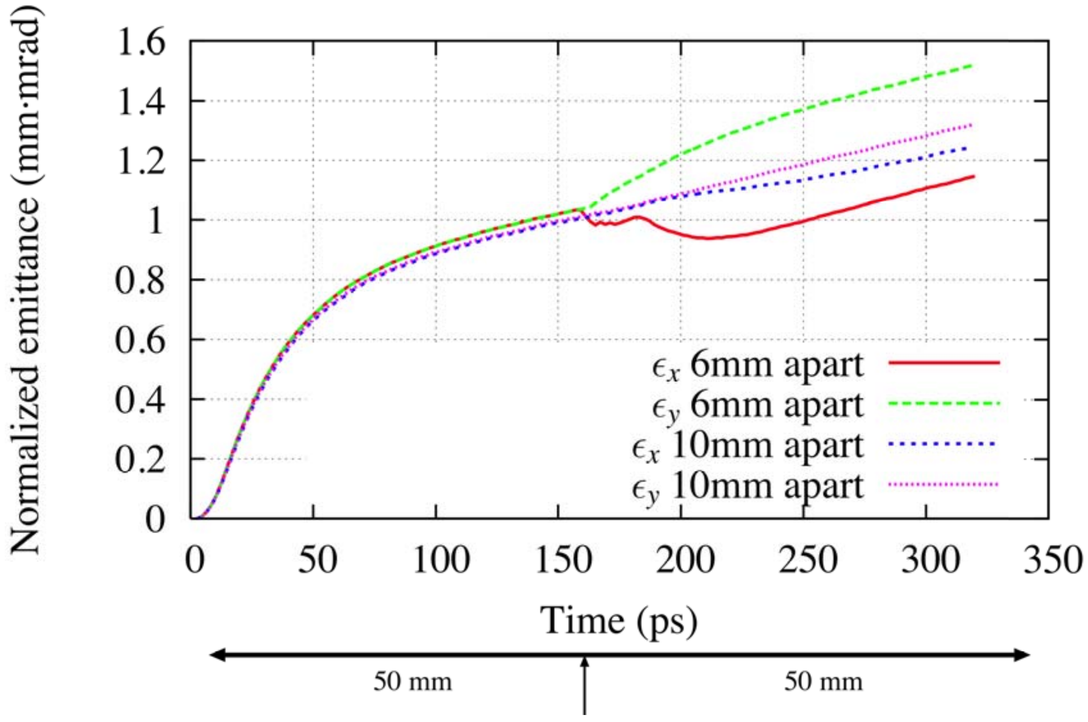


10 ps, 0.38 nC

15 ps, 0.52 nC

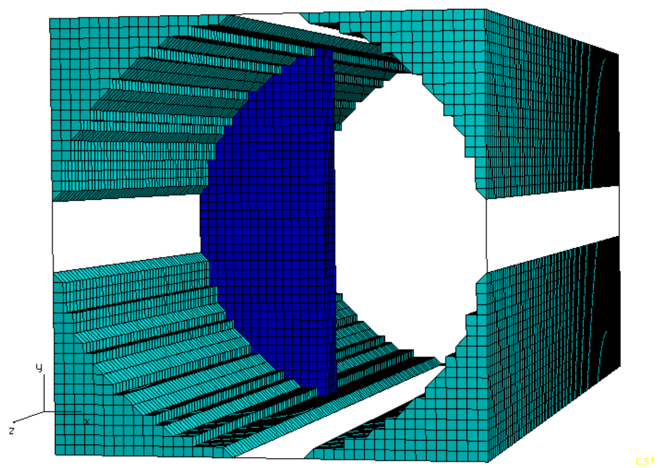
Simulation results of emittance growth under influence of normal incidence mirror installed in horizontal (x-axis)

(Behavior near by mirror in vacuum）



Position of normal incidence mirror

Beam Conditions
bunch charge = 0.83 nC
bunch length = 4.5(1σ)ps(±3σ)
beam size = 3.5(1σ)ps(±3σ)
beam energy = 3.6 MeV
initial emittance = 0 m·rad



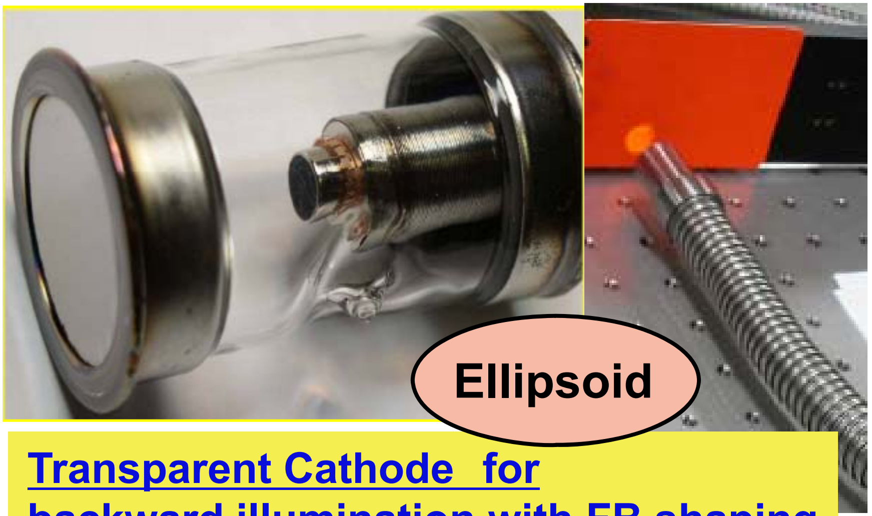
- **Simulation results reproduce that Y- emittace growth is larger than X- .**

  ⇒ **Normal incidence mirror is the cause of emittance asymmetry.**

- **When the mirror installs 10mm apart from beam axis, emittance symmetry is improved enough.**

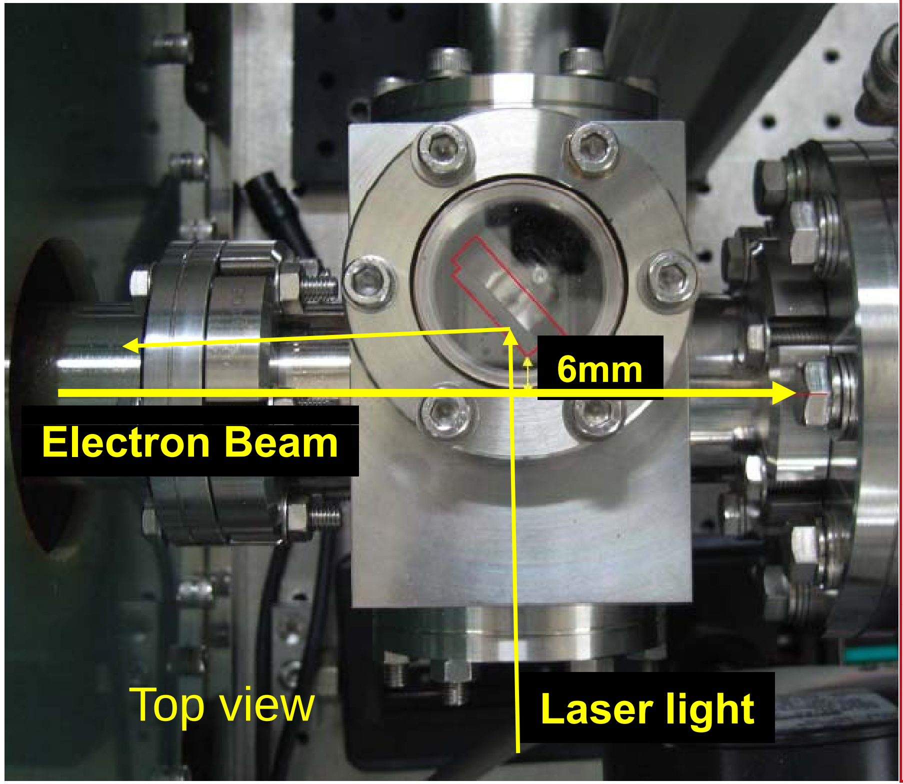
Laser Incidence methods:

- Oblique incidence
- Normal incidence
- Backward incidence
- Hollow beam incidence



Transparent Cathode for backward illumination with FB shaping

~ Influence of normal incidence mirror~



3D-Laser pulse shaping:

~ some problems as followings~

- getting more complicated
- Interference due to shaping
- Coherency of laser (kill or use)

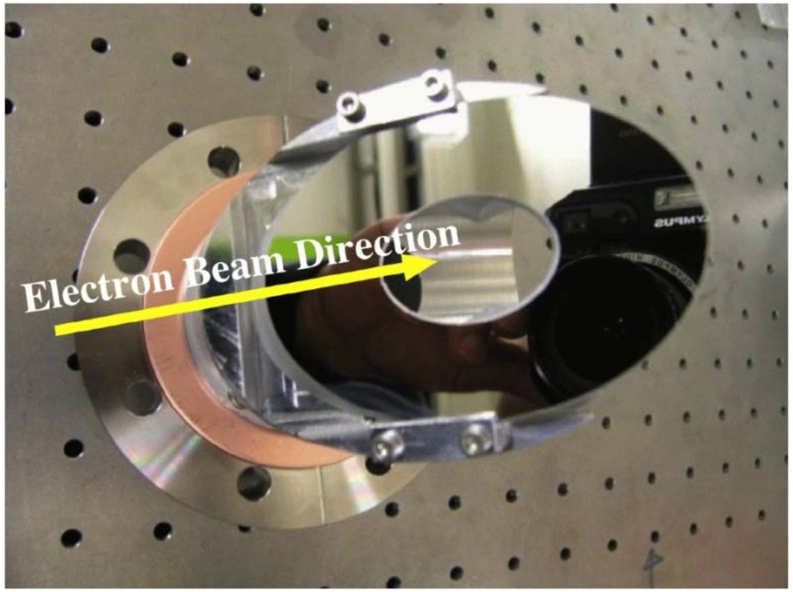
Asymmetry of transverse emittance:

~ Mirror in Vacuum is problem~

- How to minimize wake-field
- How to avoid from charging-up on mirror
- Backward illumination ~ vanishing mirror ~
- Hollow beam incidence ~ keep mirror away ~

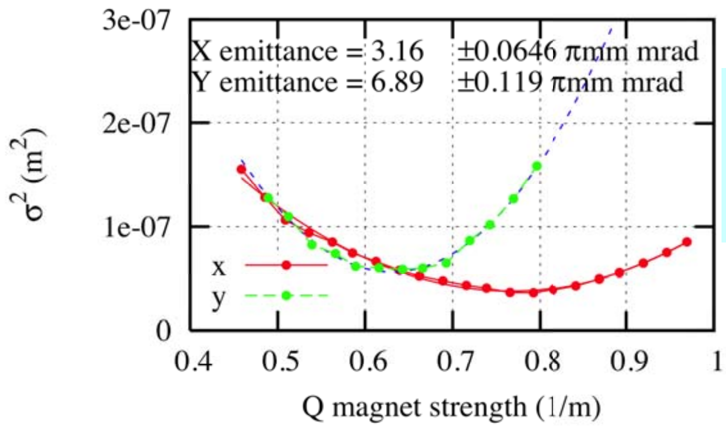
Experimental efforts for improvement of emittance symmetry I: Hollow mirror incidence

Put the mirror away form beam axis (> 10mm). → Hollow mirror with 20-mm hole

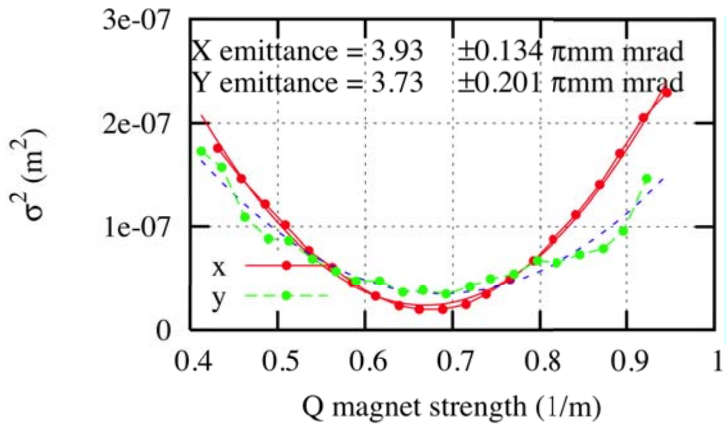


- Suppress wake-field effect
  ⇒ Mirror hole for passage of electron bunch : φ20mm

- Keeping symmetry for electron bunch
  ⇒ Hollow mirror



Conventional normal incidence mirror

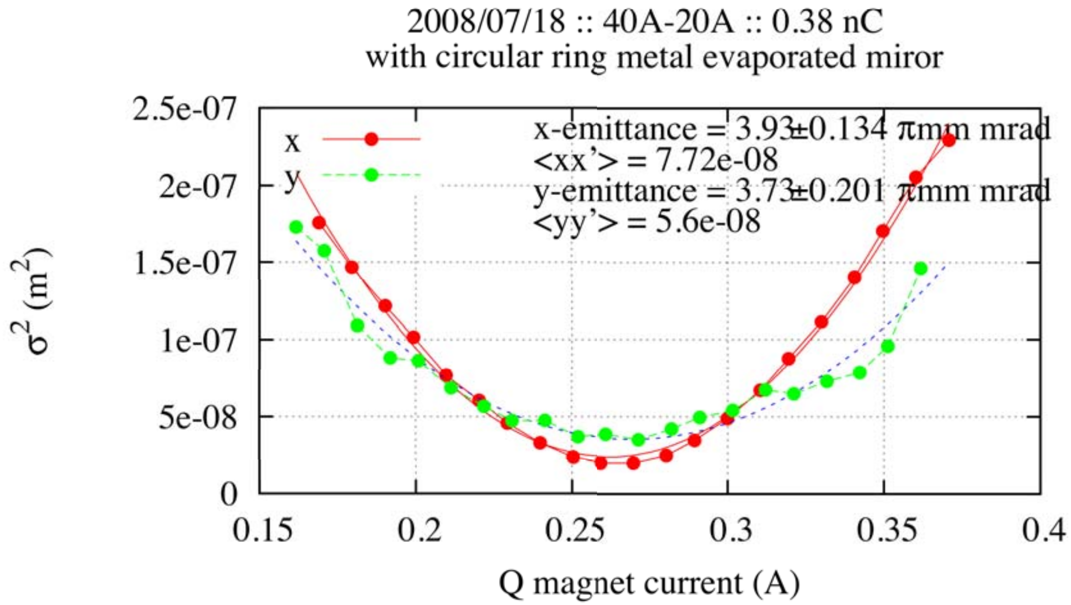


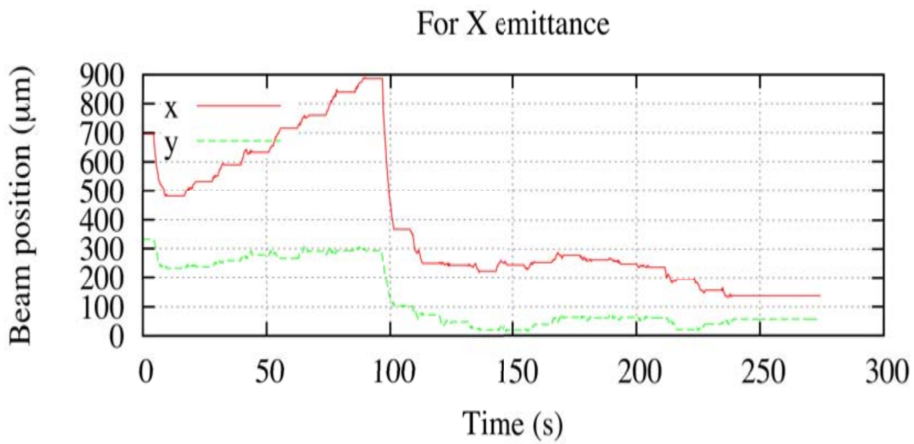
Metal hollow mirror with glass substrate (Al-coating just on the mirror surface)

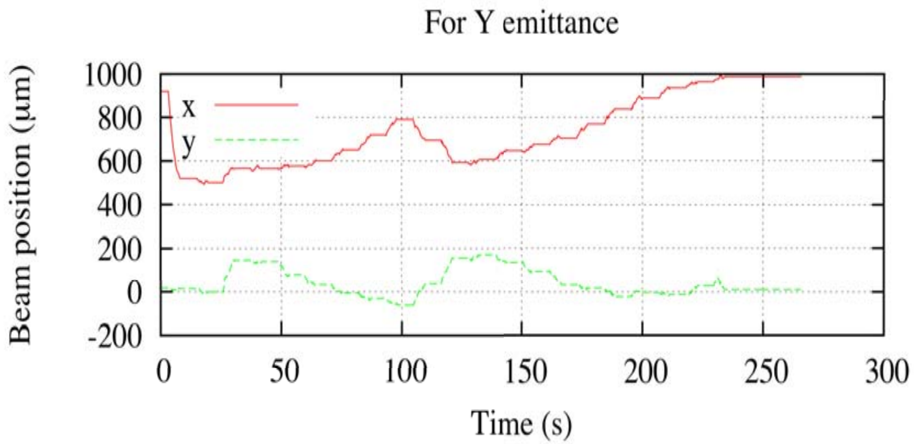
○ Symmetry between X &Y got better!

× however, curve fitting is not good.

Fluctuation of beam positions during emittance measurements







The cause of fluctuation:

Charge-up on the glass substrate surface due to dark current

"Full-Metal-Jacket" glass substrate with silver metal clay to avoid form charge-up

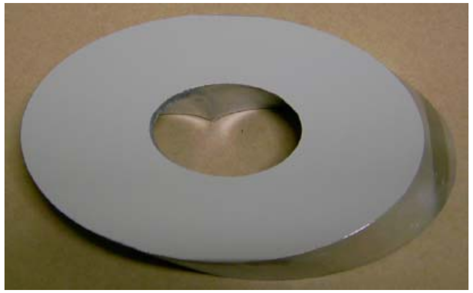
The wall of glass substrate hole was not covered with metal.

⇒ The cause of charge-up

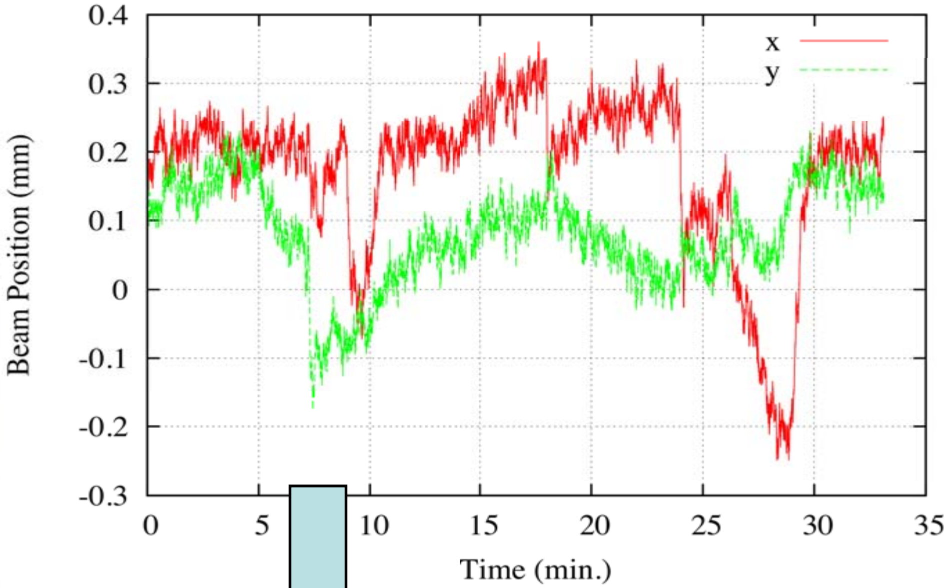
Whole metal cover of glass substrate with silver metal clay

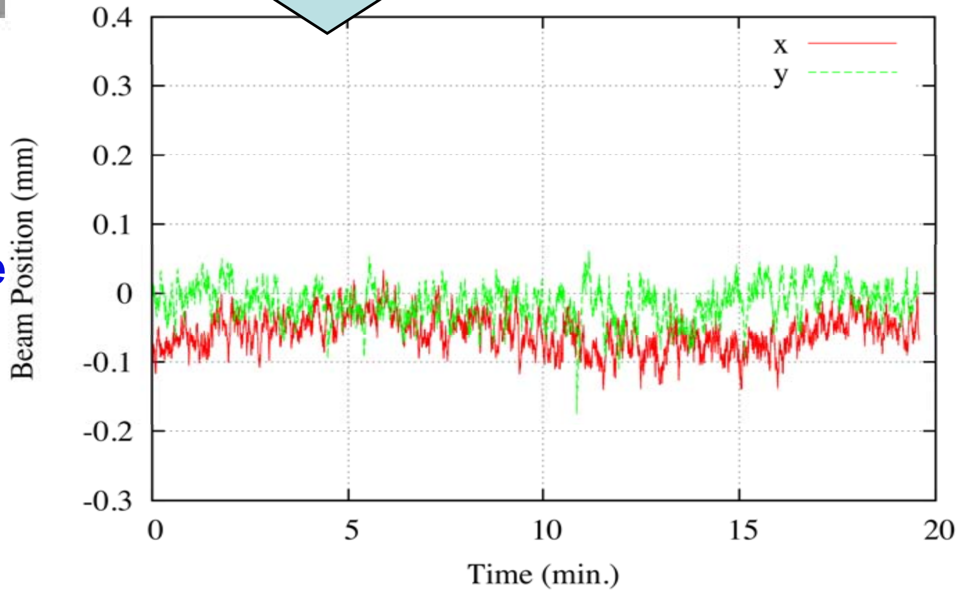
○ The fluctuation of beam position got better and reliable

× The vacuum got worse.
⇒ whole metal mirror substrate

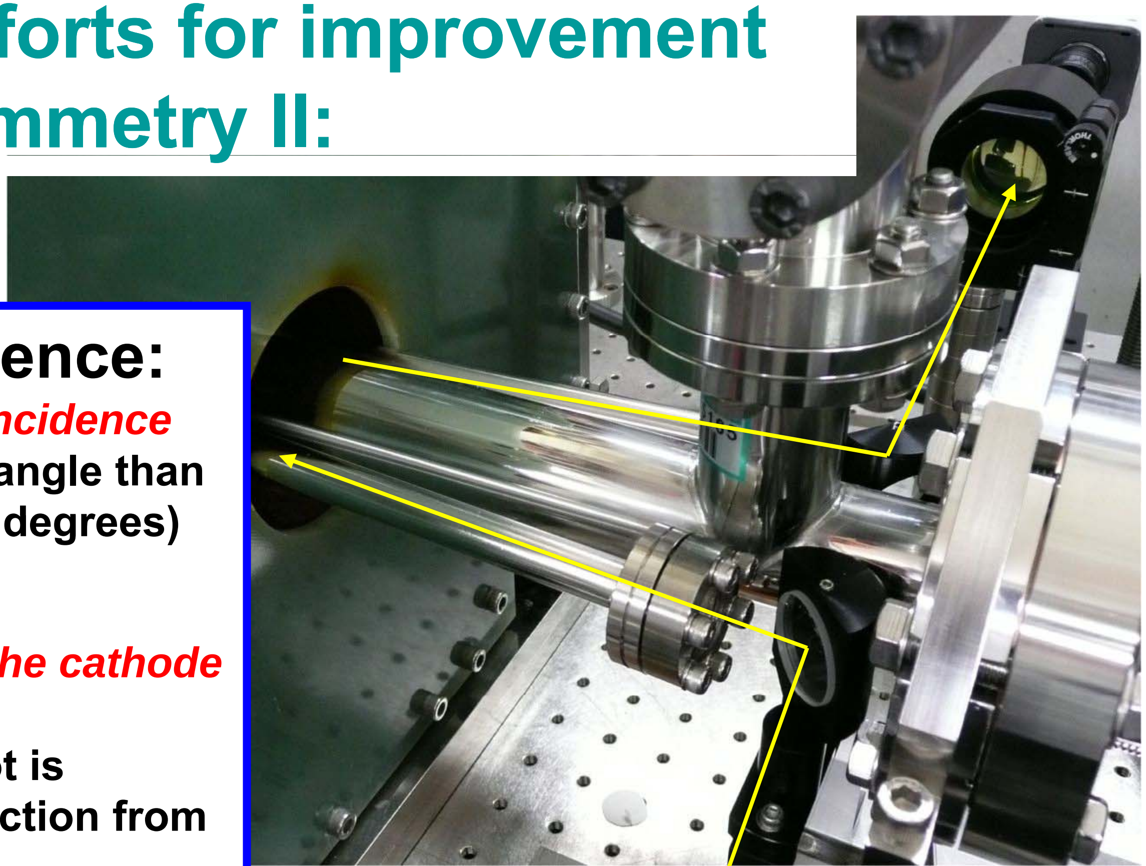


Beam position at the entrance of the accelerator tube





Experimental efforts for improvement of emittance symmetry II:



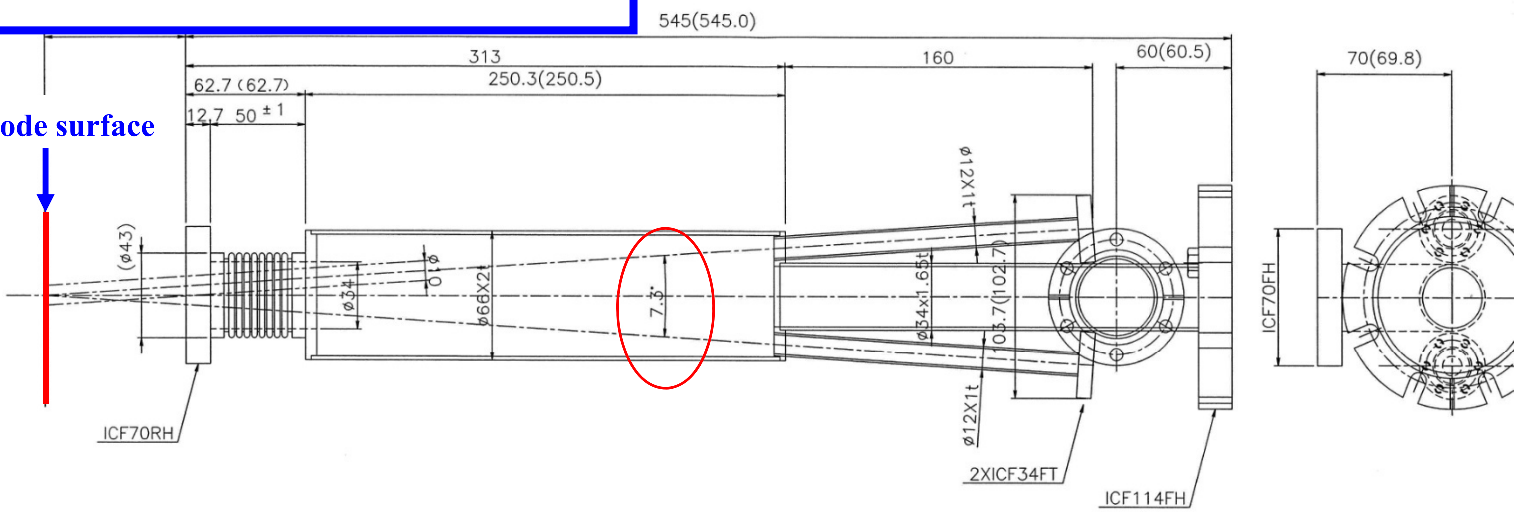
New Oblique Incidence:

4 degrees (3.65 degrees) incidence

- a little larger incident angle than normal incidence (1.4 degrees)

Final transport mirror to the cathode installs out of Vacuum

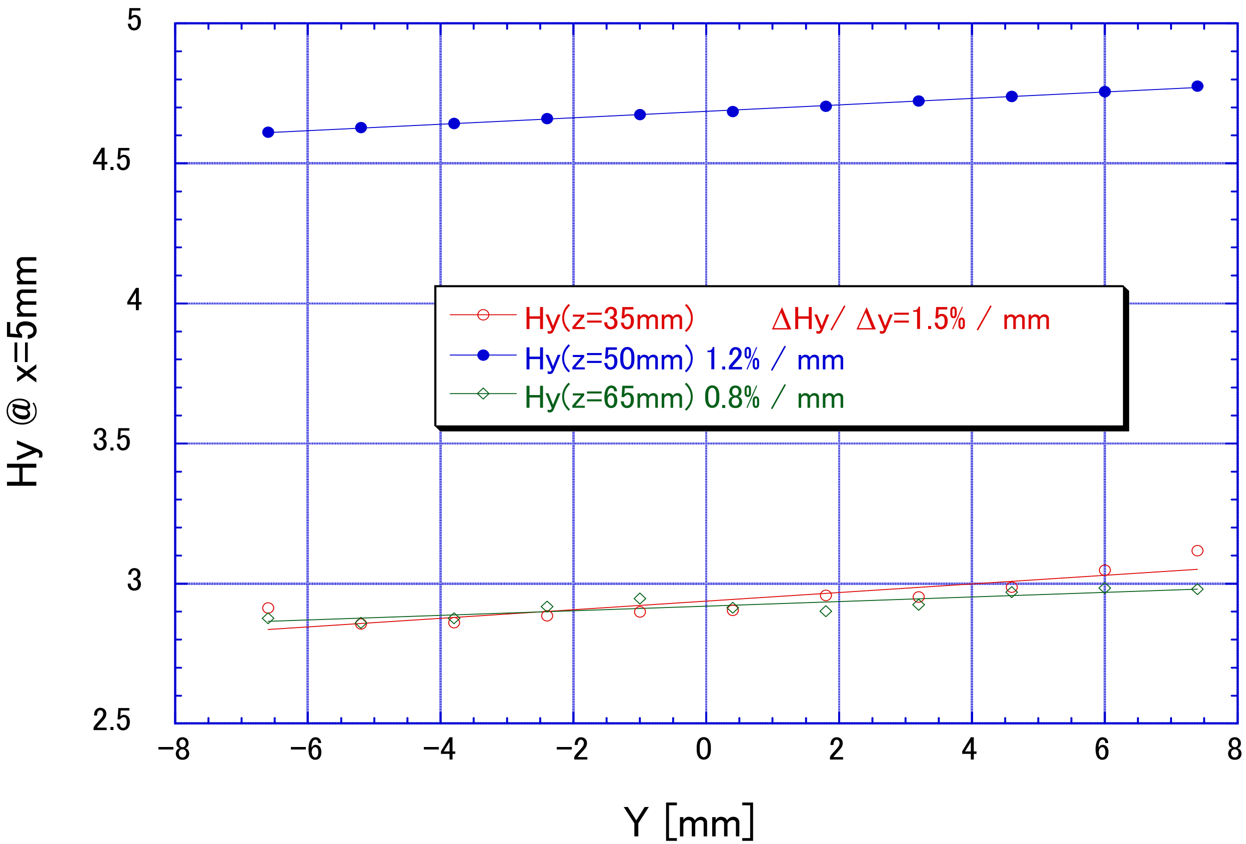
- Laser illuminating spot is monitored with a reflection from the cathode.

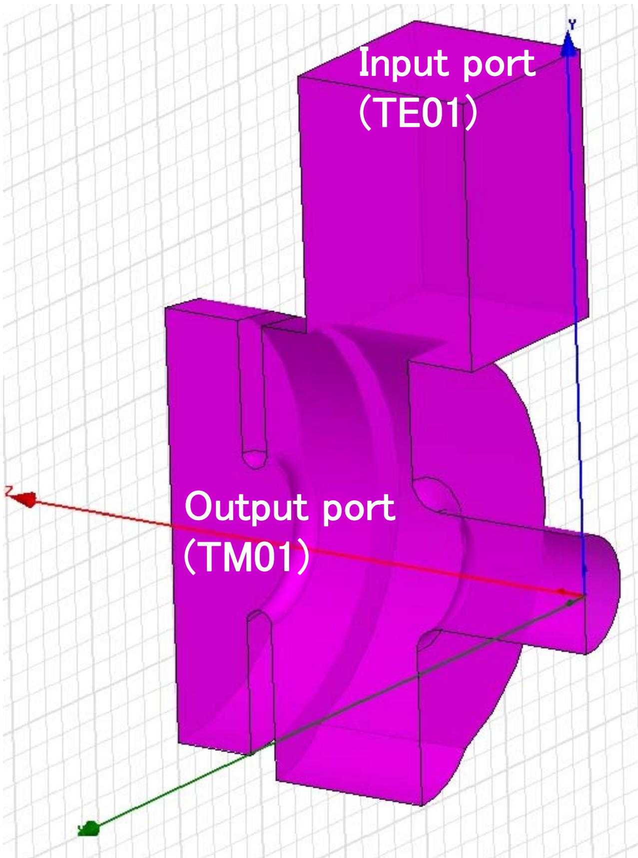


The other possible causes of X- and Y- emittance asymmetry:

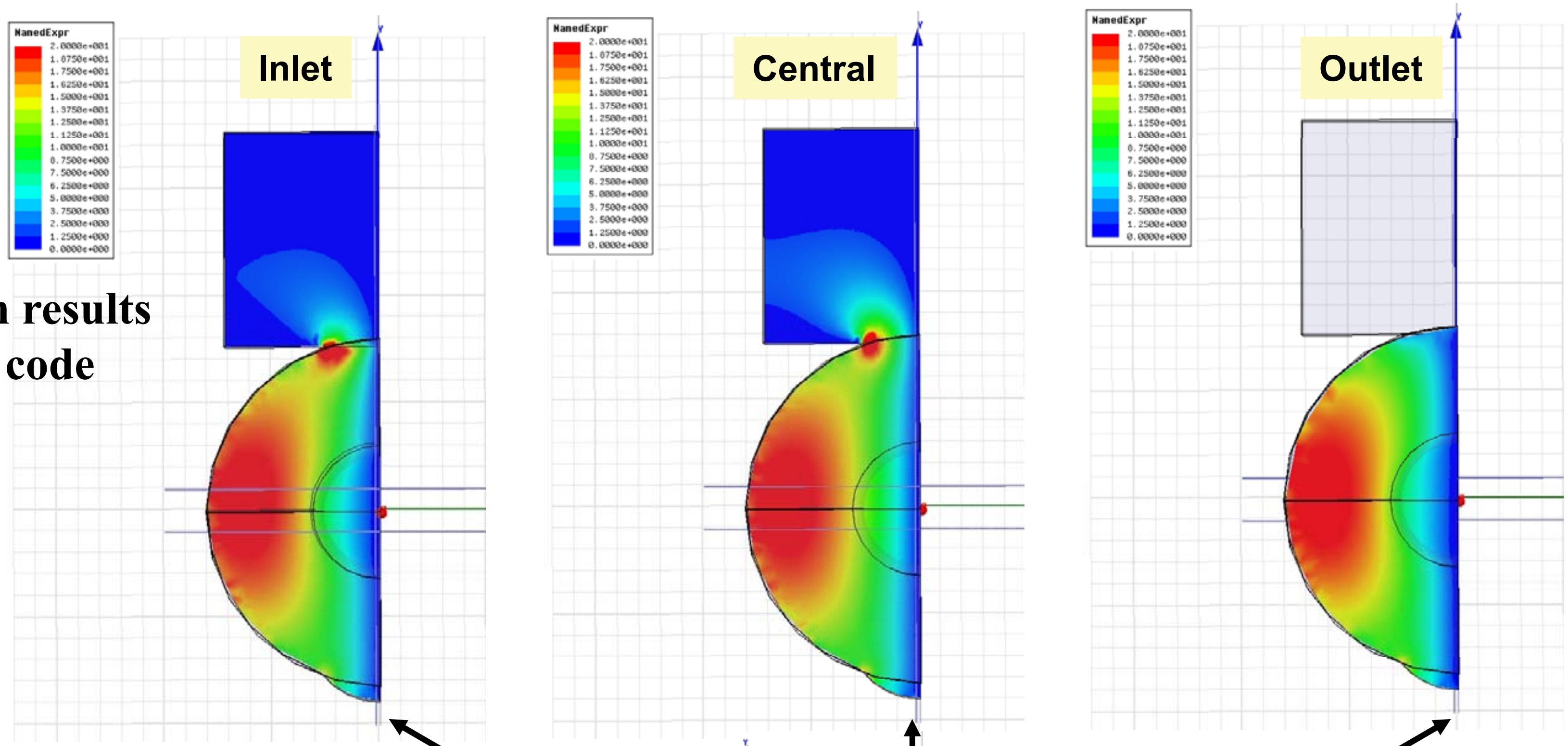
- Residual solenoid field at the cathode together with asymmetrical focusing between X and Y (at the coupler of acc. tube or optics):

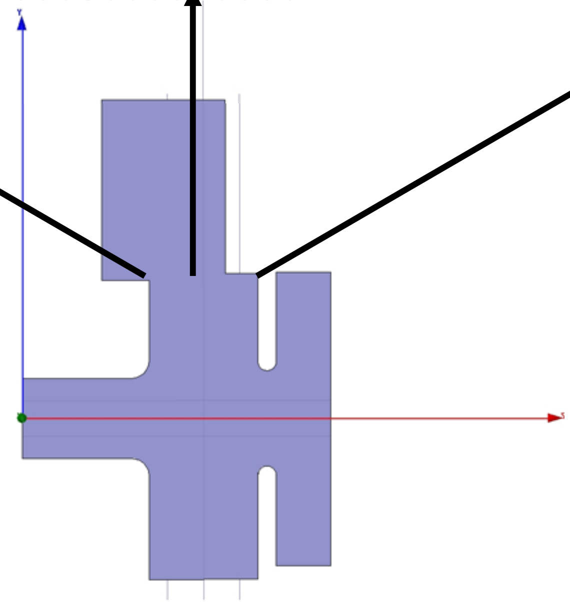
- Asymmetry field at the coupler of accelerator tube :



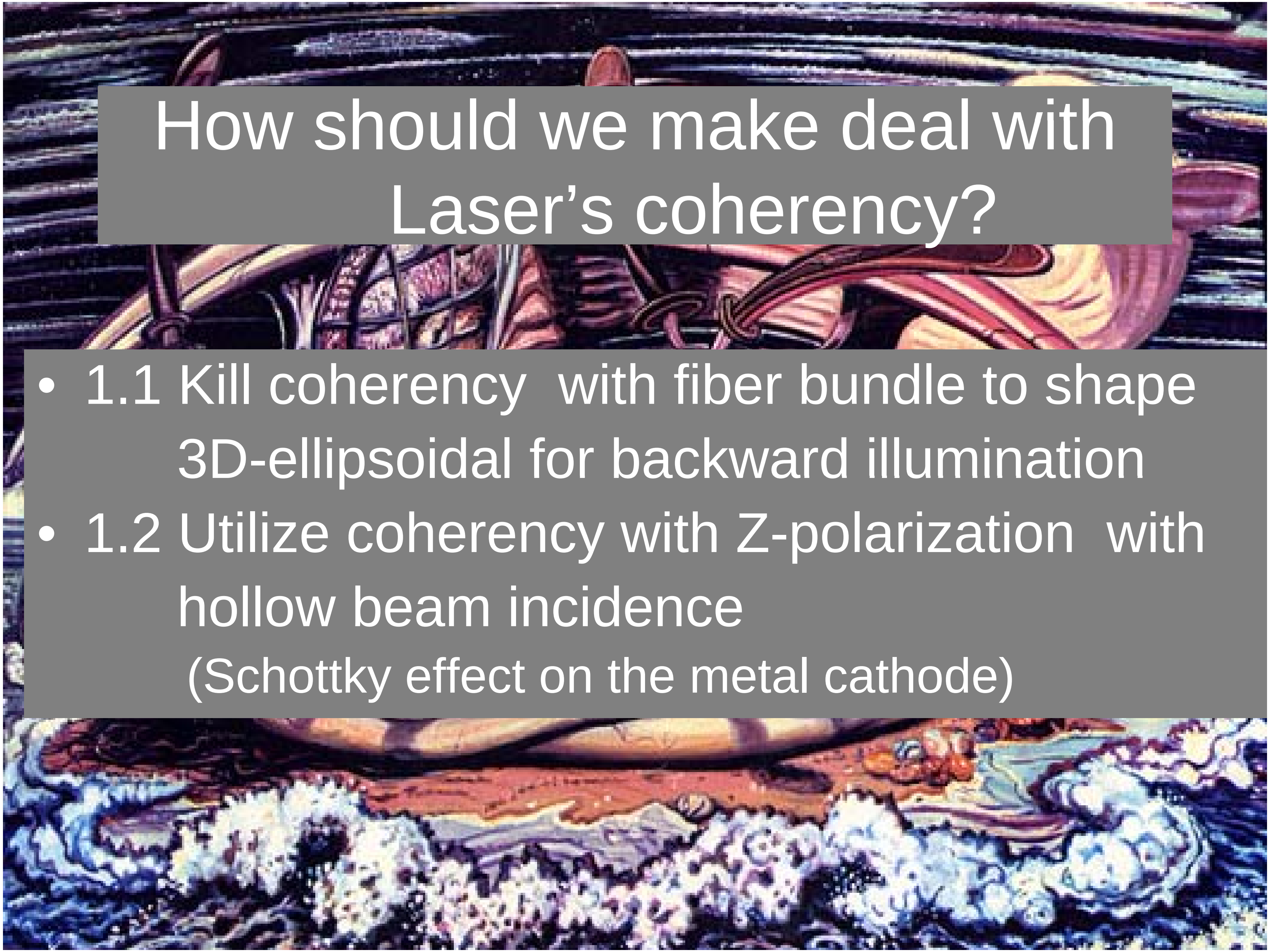


Simulation results by HFSS code





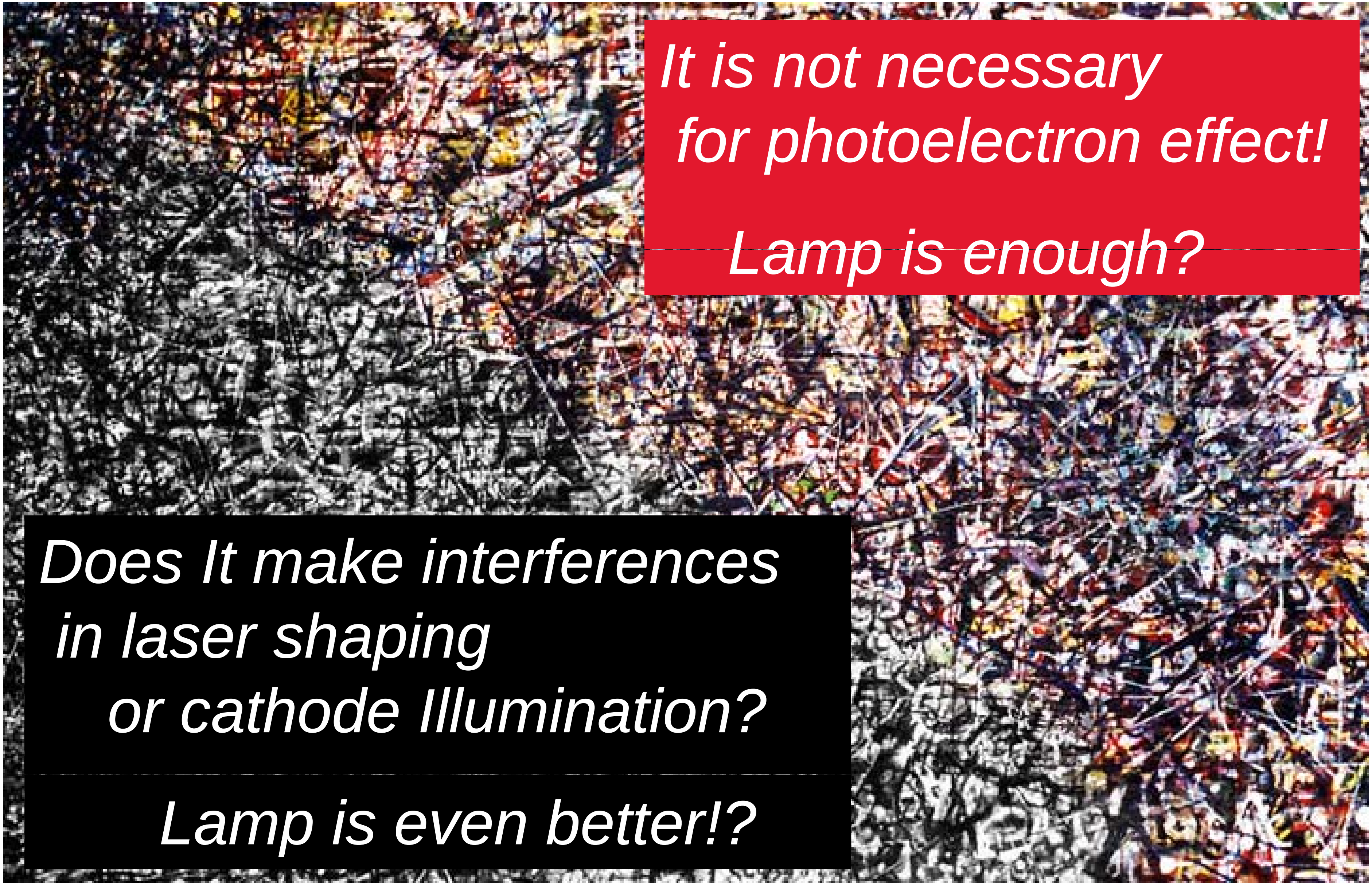
A little coupling of emittance exists, however it should be negligible.



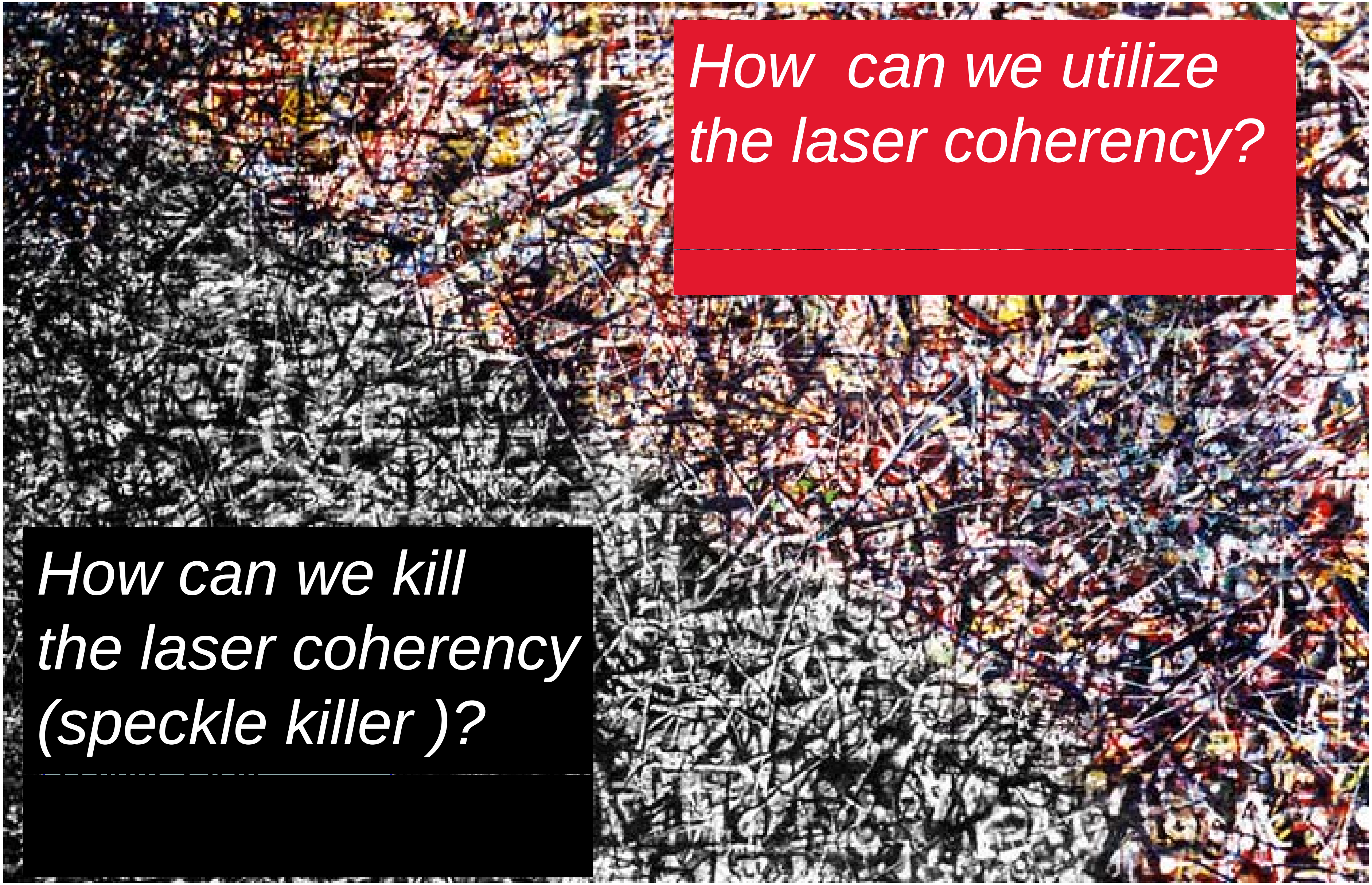
How should we make deal with Laser's coherency?

- 1.1 Kill coherency with fiber bundle to shape 3D-ellipsoidal for backward illumination
- 1.2 Utilize coherency with Z-polarization with hollow beam incidence
  (Schottky effect on the metal cathode)

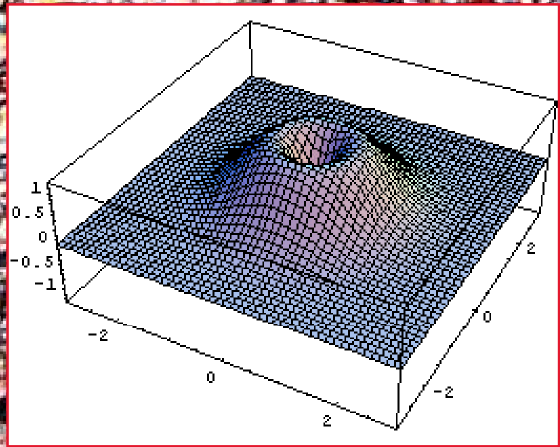
Coherency of Laser is good or bad!?



Coherency of Laser is good or bad!?



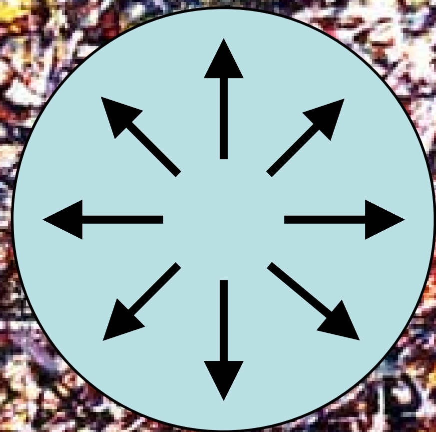
Coherency of Laser is good or bad!?

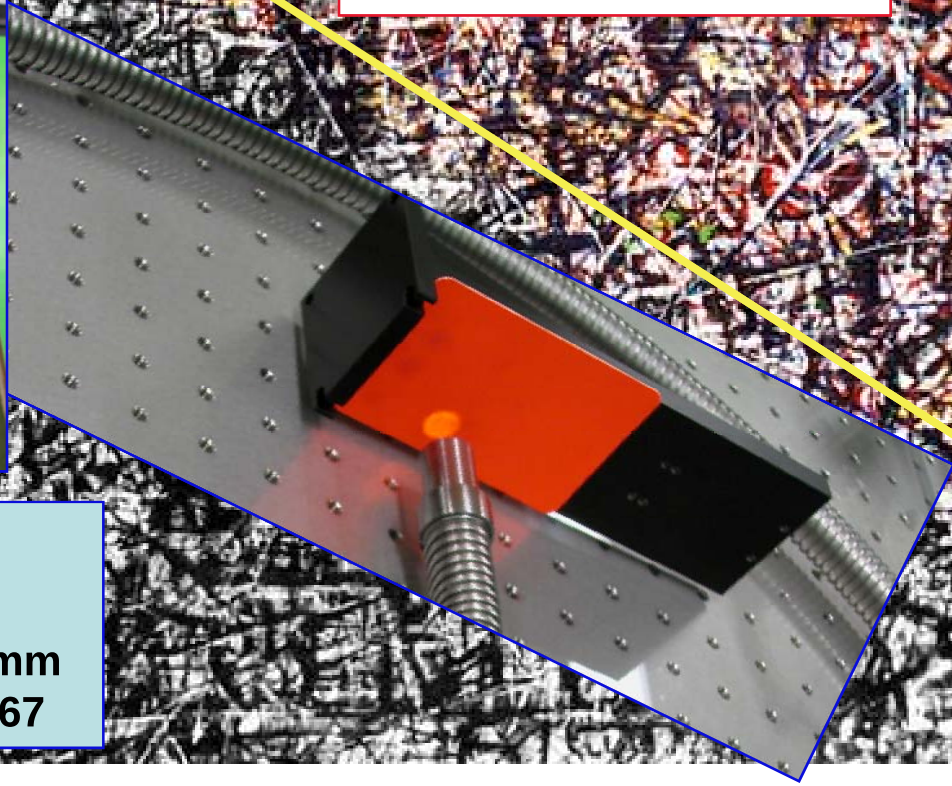


Z-polarization:

Field: ~GV/ m
Schottky：~2 eV

Radial polarization：





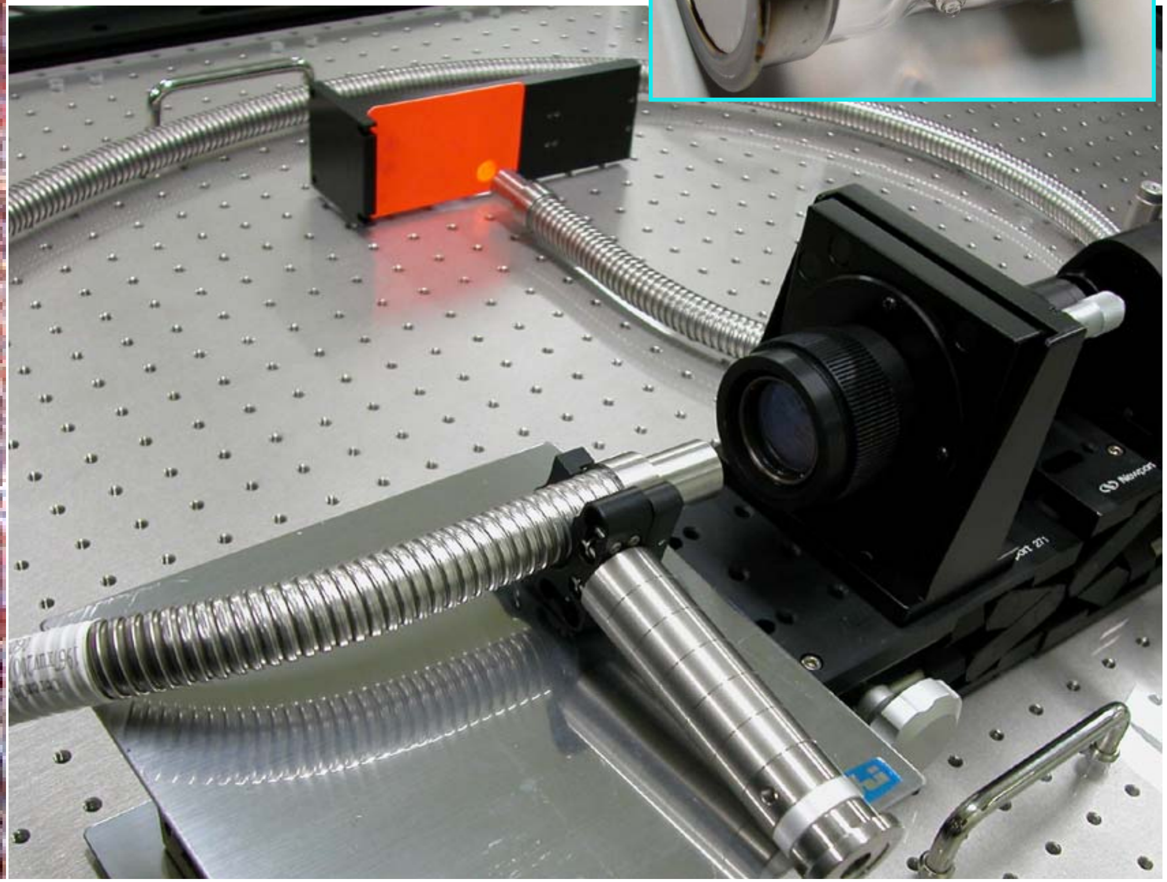
Fiber Bundle:

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

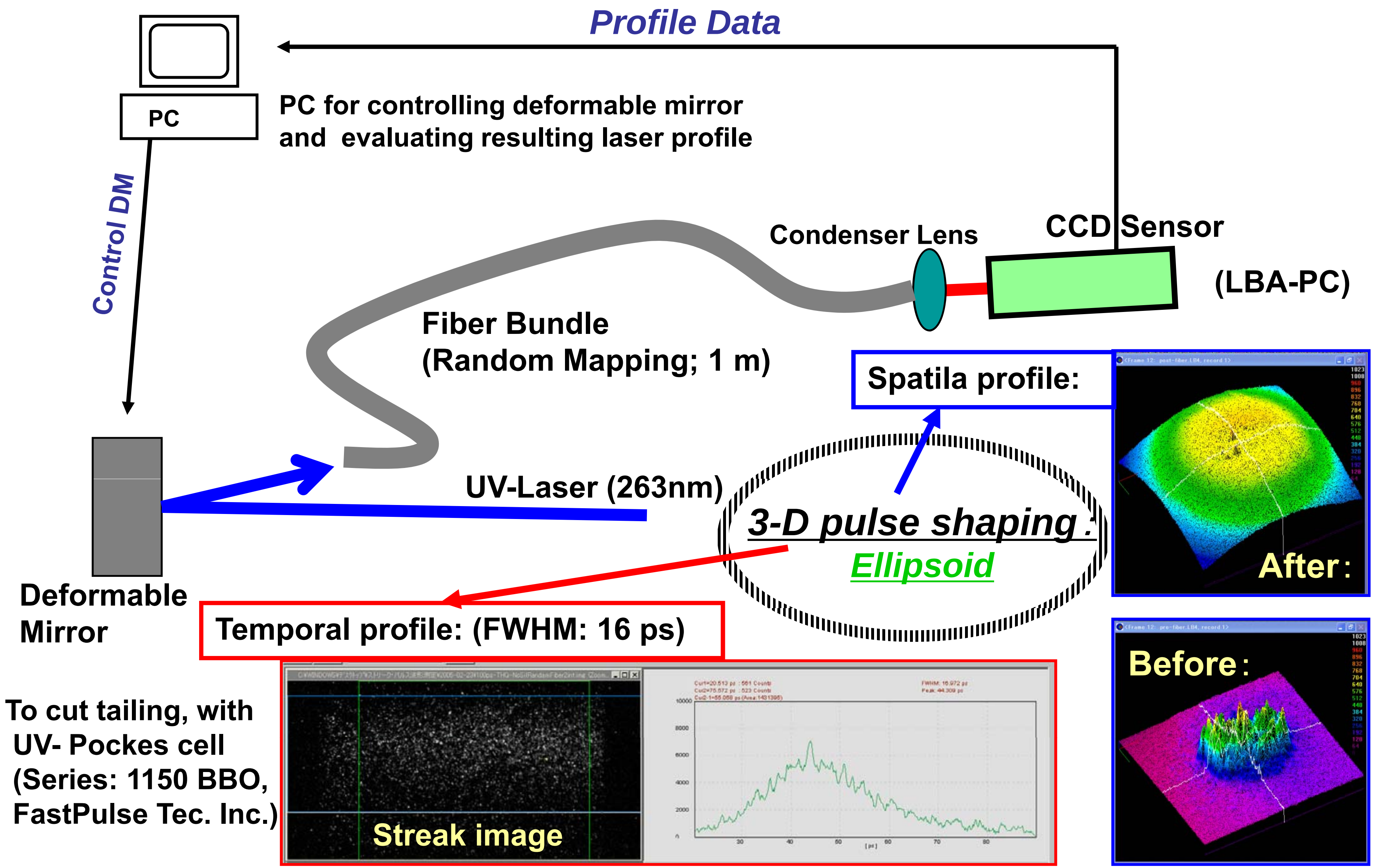
Kill) Fiber bundle laser profile homogenizer with backward illumination (transparent cathode)

~ Transparent Cathode with Fiber Bundle ~

Pulse Stacking with 2,000 different Optical Passes



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



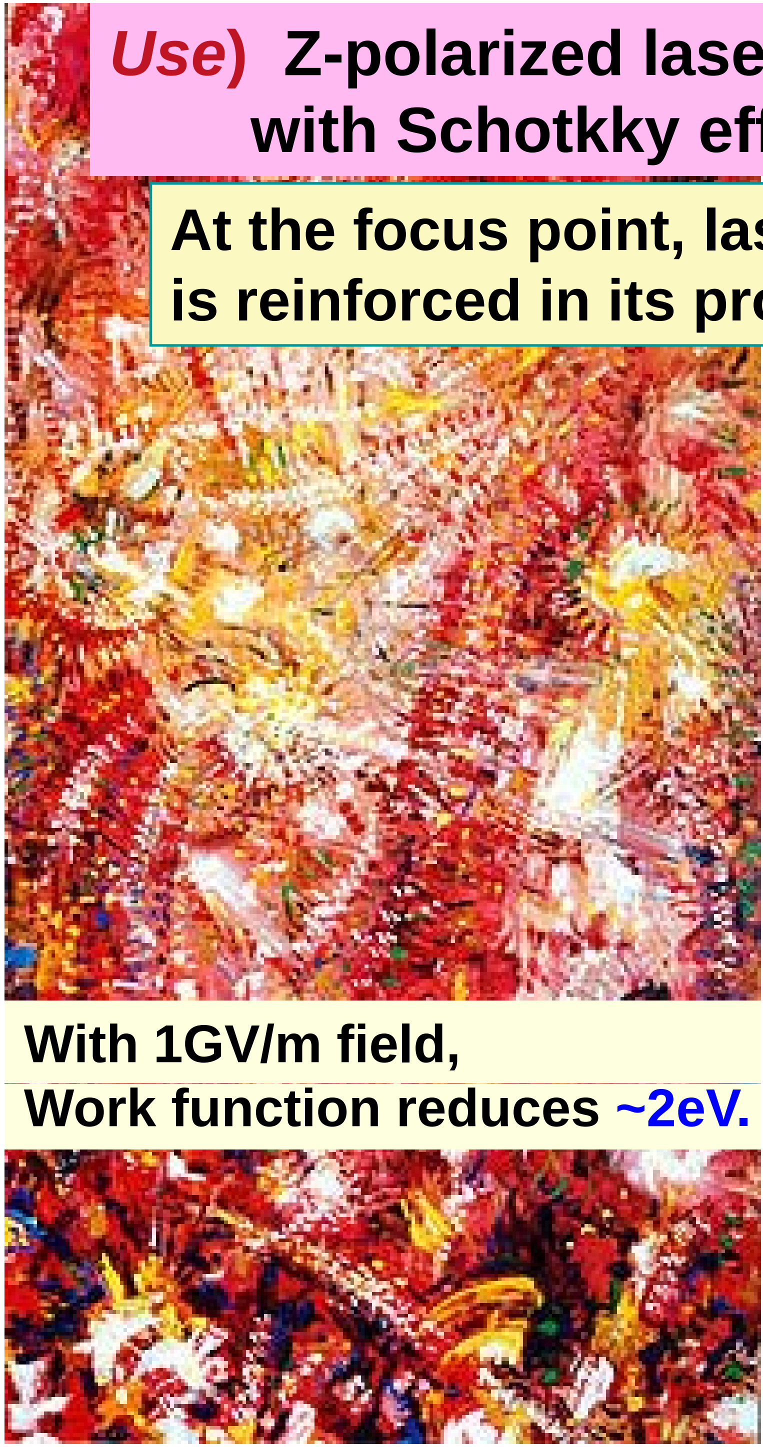
Short Summary of Laser shaping

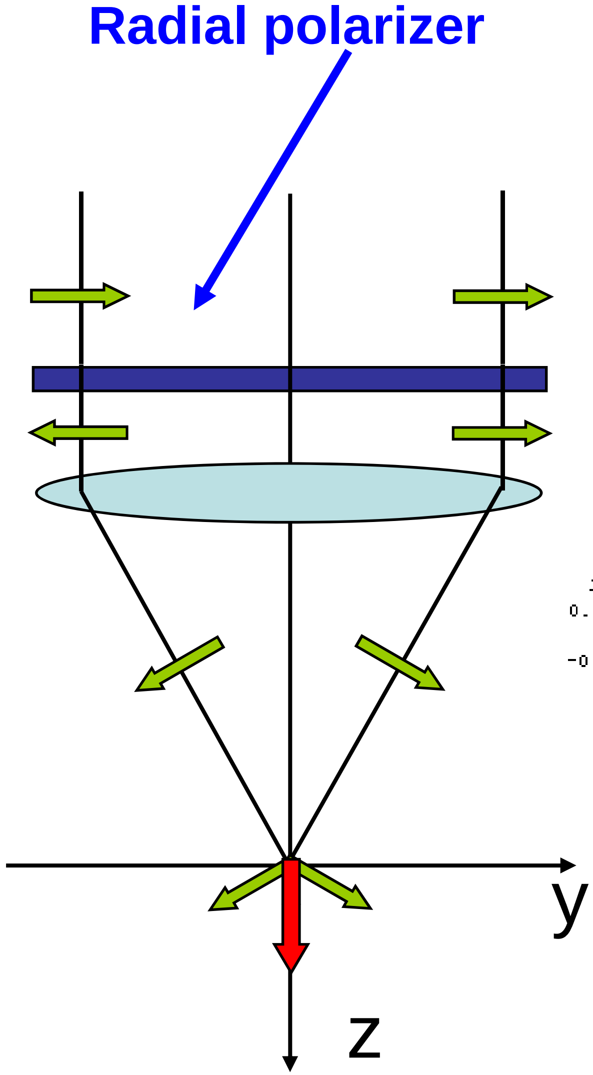
- Shaping with computer-aided deformable mirror could generate Flattop. It is very flexible to optimize the spatial profile with genetic algorithm. Combining with pulse stacker, 3D- laser pulse shaper was completed.
- Fiber Bundle is ideal as a 3D-shaper (patent)
  - It is very simple to shape : You 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

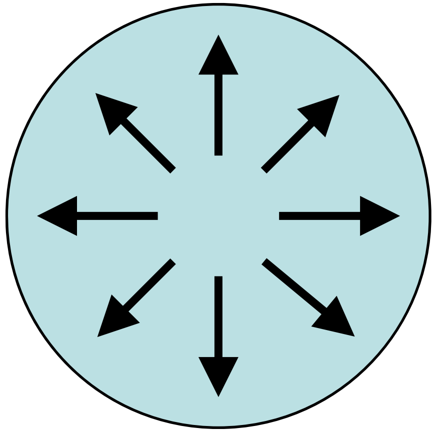
    It is possible to use as 3D-shaper down to 60 nJ/pulse.
- Transparent cathode for shaping complex system with fixed fiber bundle & adjustable deformable mirror might have a lot of possibilities with fine tuning.

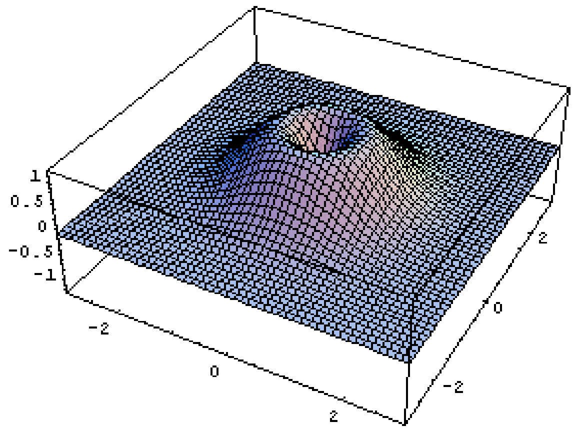
Use) Z-polarized laser on the cathode & field emission with Schottky effect (It's not proved yet!)

At the focus point, laser electrical field is reinforced in its propagating direction





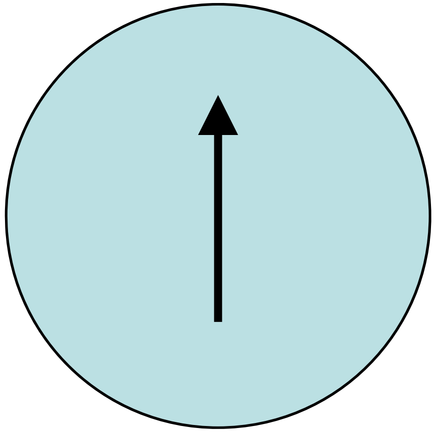




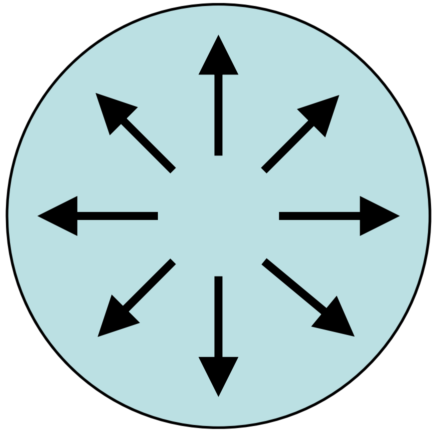
With 1GV/m field,
Work function reduces ~2eV.

Radial Polarization beam

Cross section of laser beam



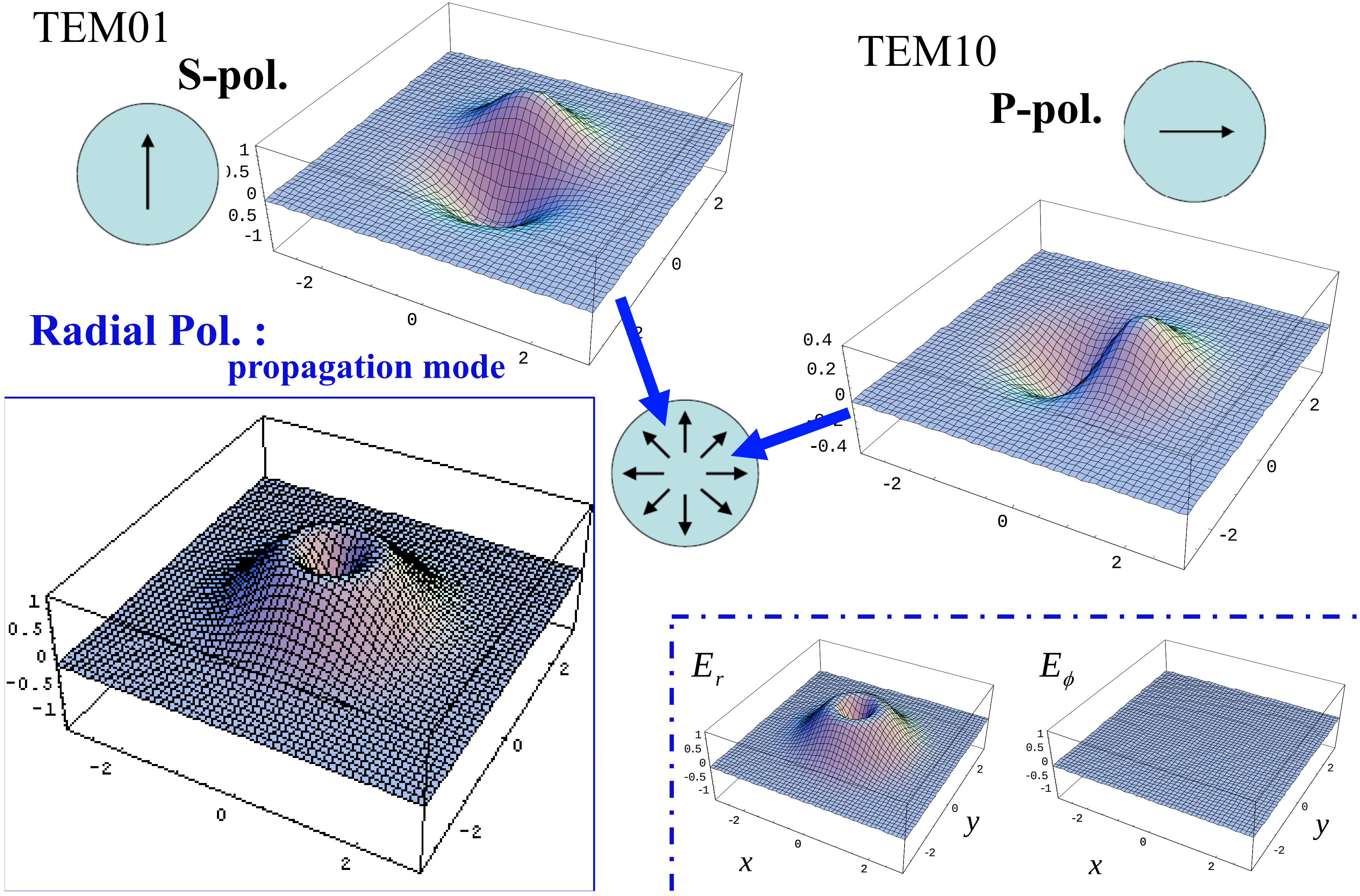
Linear polarized beam



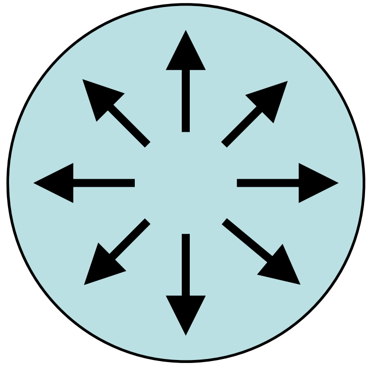
Radial polarized beam

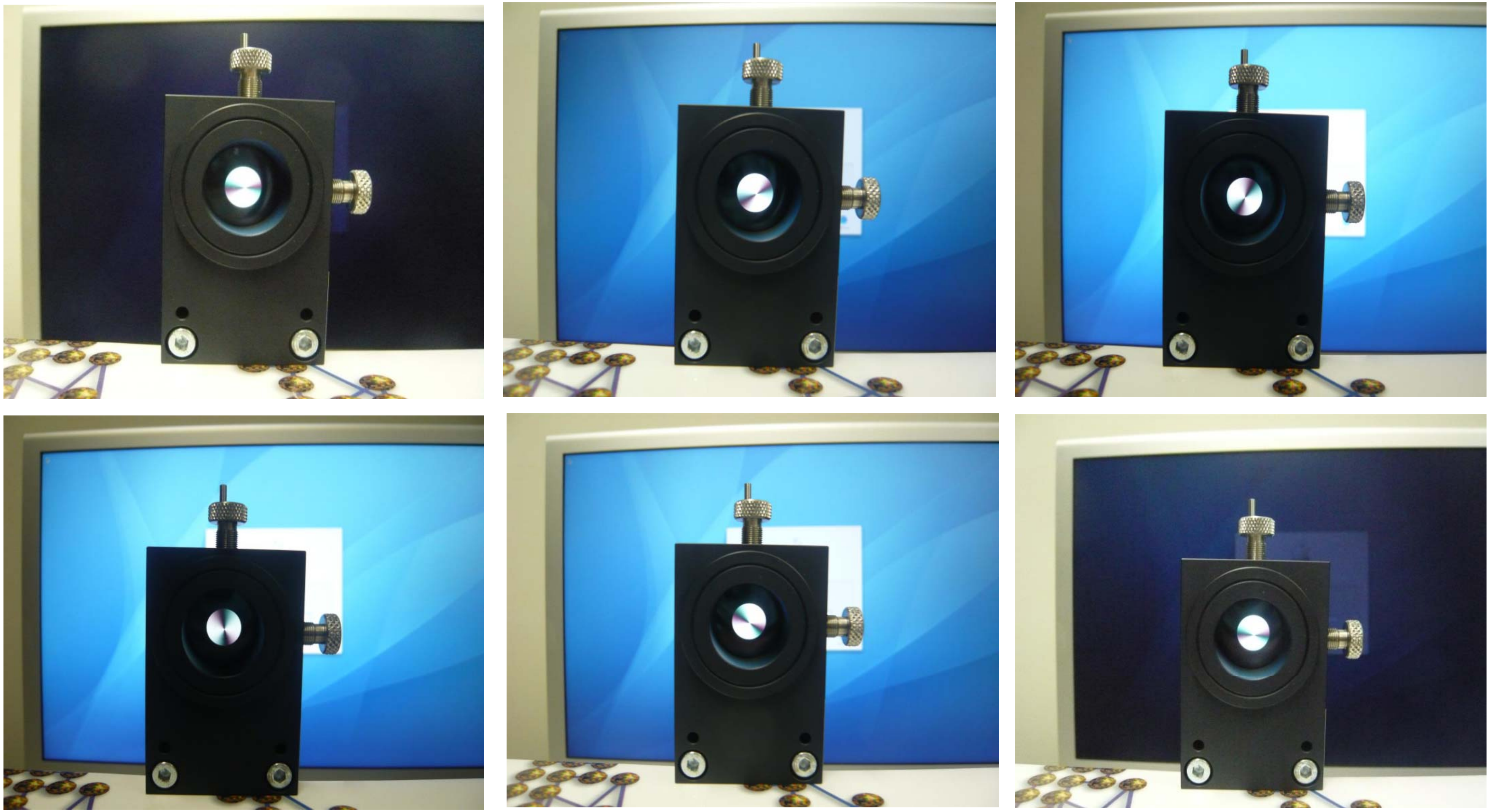
The radial polarized beam is superposition of $\pi/2$ phase-shifted TEM_{01} and TEM_{10} mode in the case of polarization direction vertical each other.

Radial Polarization laser beam



Demonstration of Radial polarization with rotation of polarizer

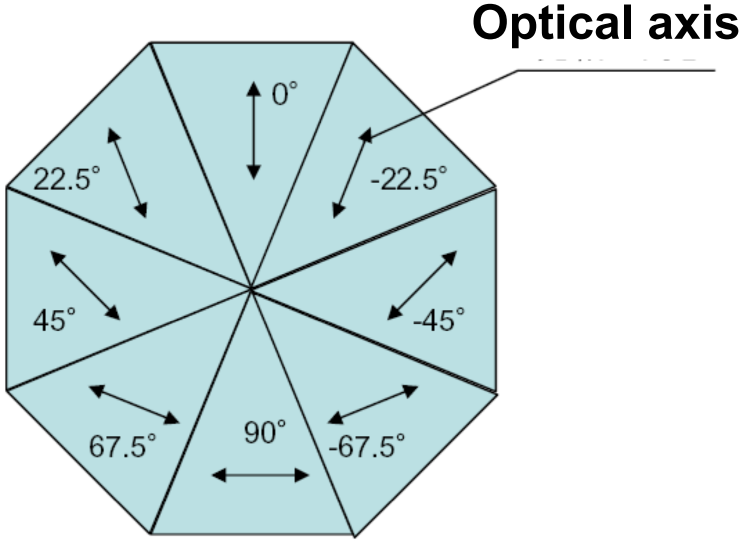




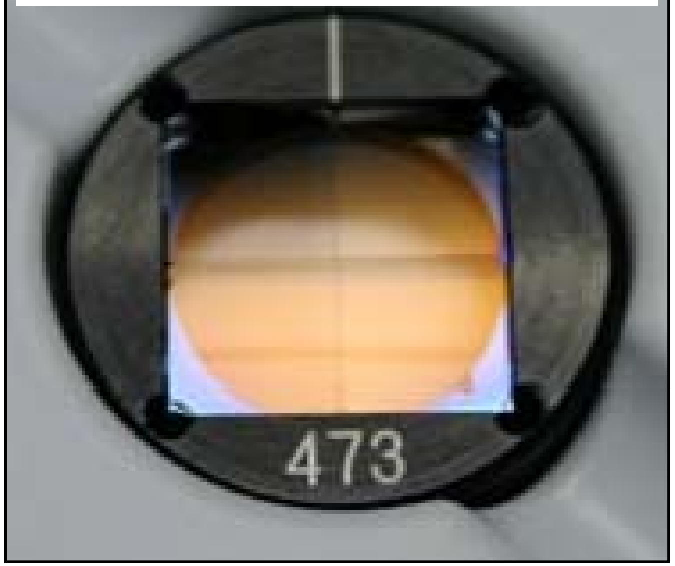
Simplest radial polarizer: divided waveplate

(a) 8-divided waveplate

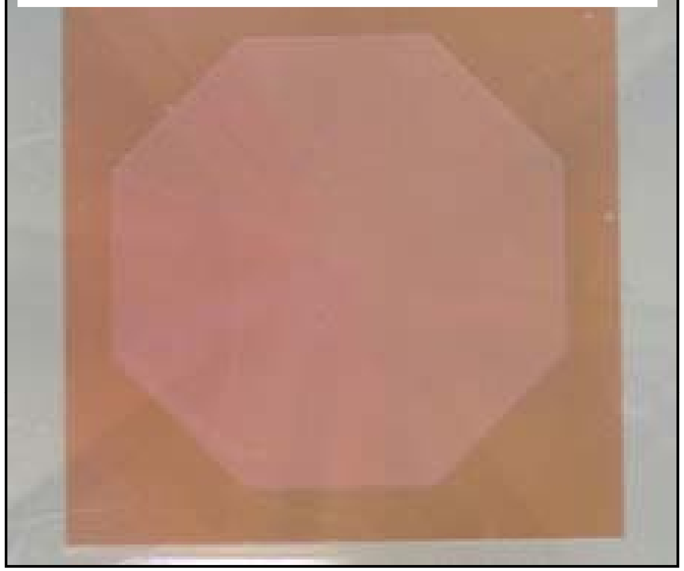
(b) 8-divided waveplate



(c) 4-divided waveplate

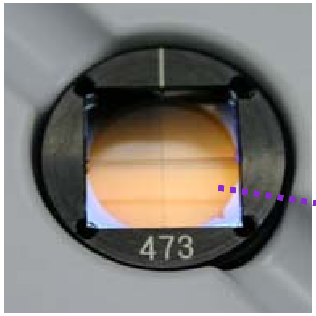


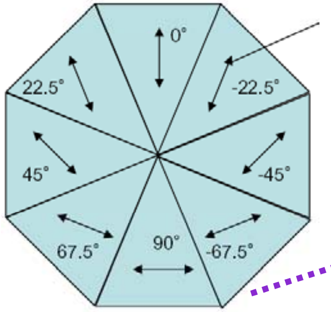
(d) 8-divided waveplate

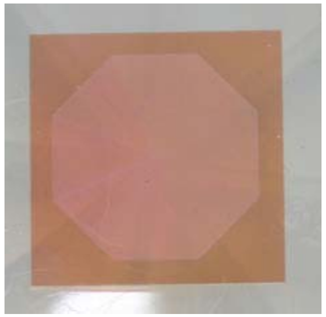


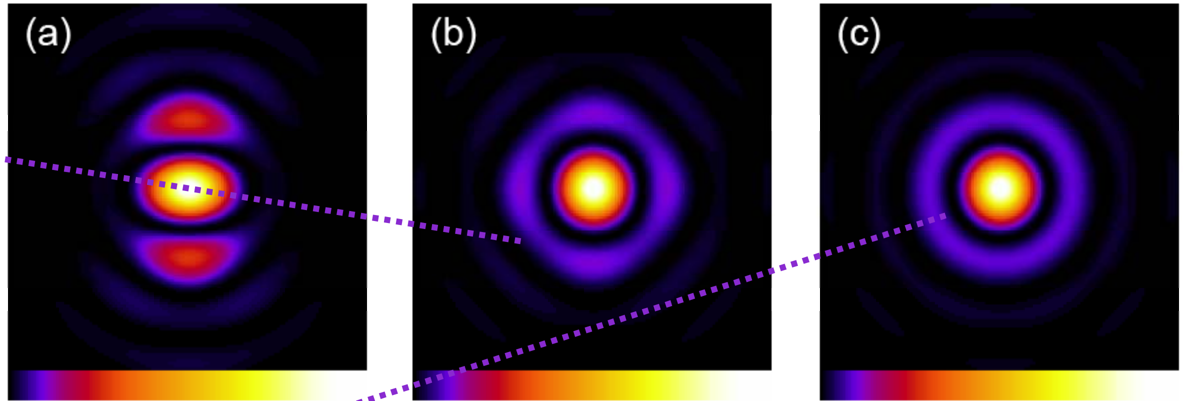
Z-polarization field on the cathode:

Divided number(2~32) dependence

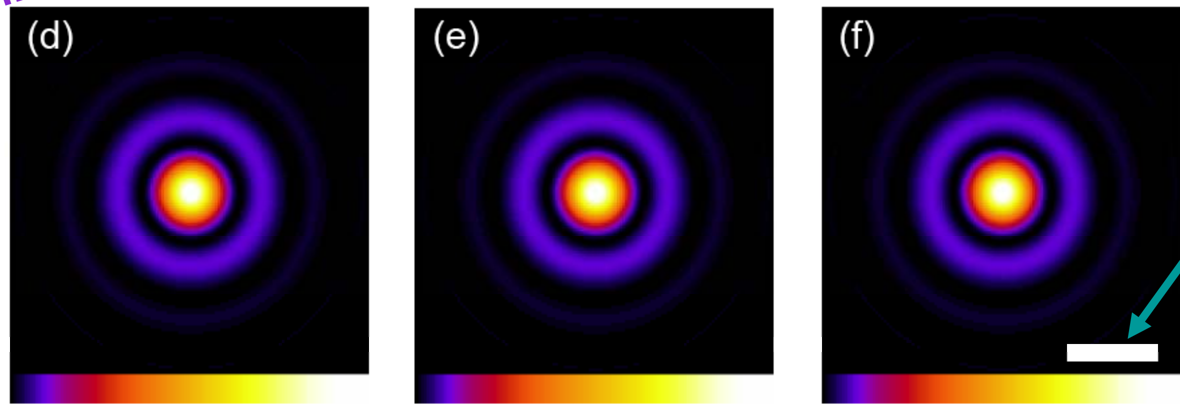








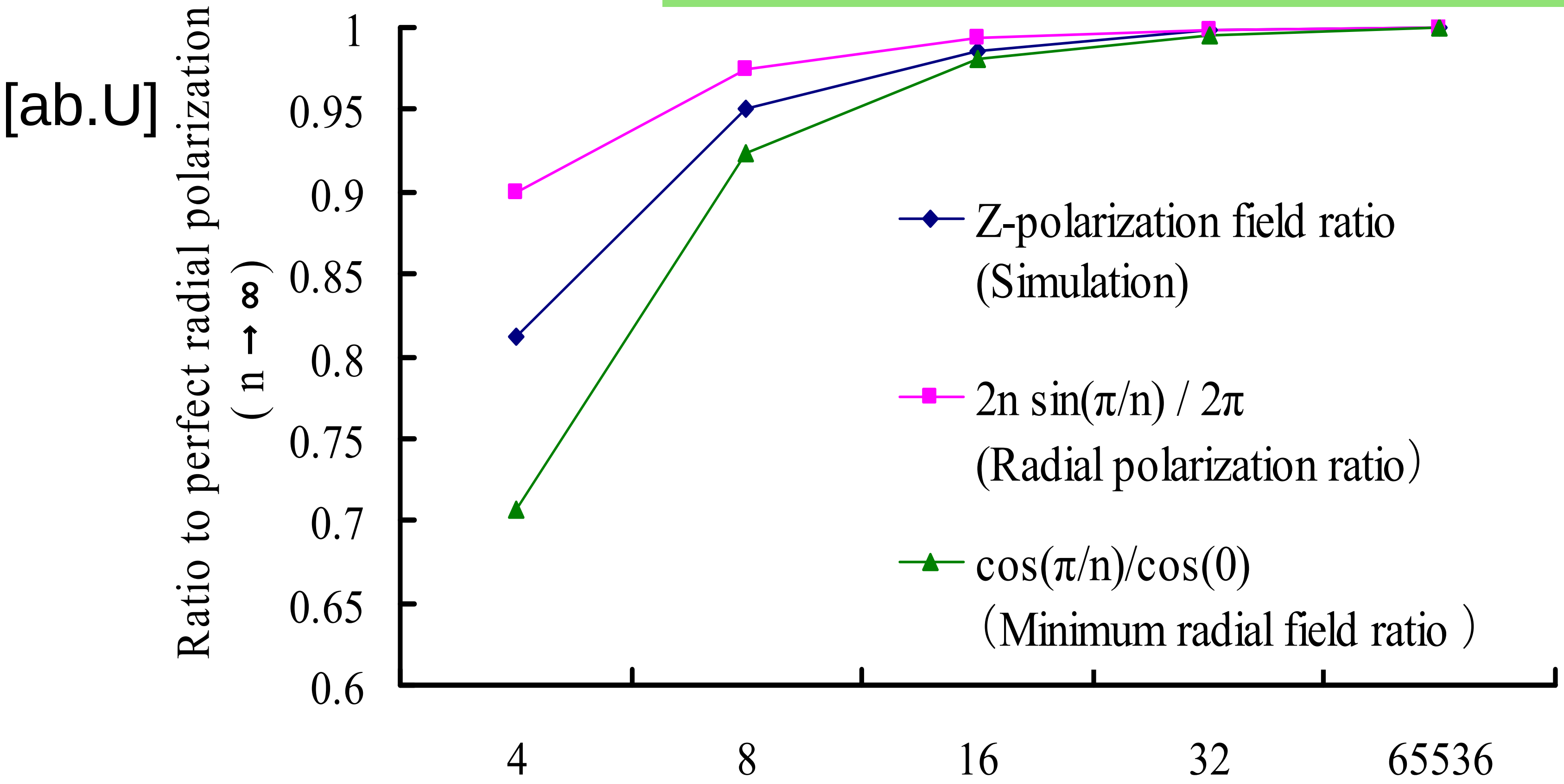
Scale bar is 7.5μm @790nm, NA=0.1 (Flattop incidence)



Using divided waveplate, the distribution of strength of Z-polarization field $|E|^2$: (a)2-divied, (b)4-divided, (c)8-divided, (d)16-divided, (e)32-divided, (f) perfect radial polarization (n: infinity)

Z-polarization ratio with divided waveplate

More than n=8, ideal radial polarization



Numerical Aperture: NA

- The strength of Z-polarization field $\propto$ **1/(Wavelnrgth:λ)^2**
- The strength of Z-polarization field $\propto$ **(NA)^2**

  $\propto$ **1/(Focus length)^2**

Water bag: Luiten scheme（Evolution of ellipsoid？）

<u>If it works, we can generate ultra-low emittance.</u>

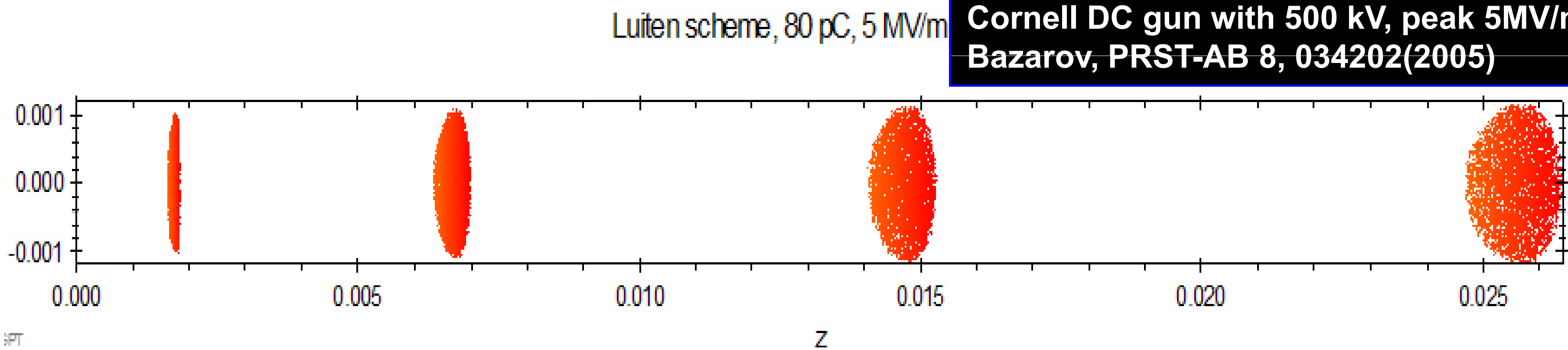
Idea: Use "pancake" laser pulse, allow beam to self-evolve to ideal ellipse
Proposed by Serafiniin 1997; again by Luitenin 2004.

We can start from femtosecond pulse at the cathode.

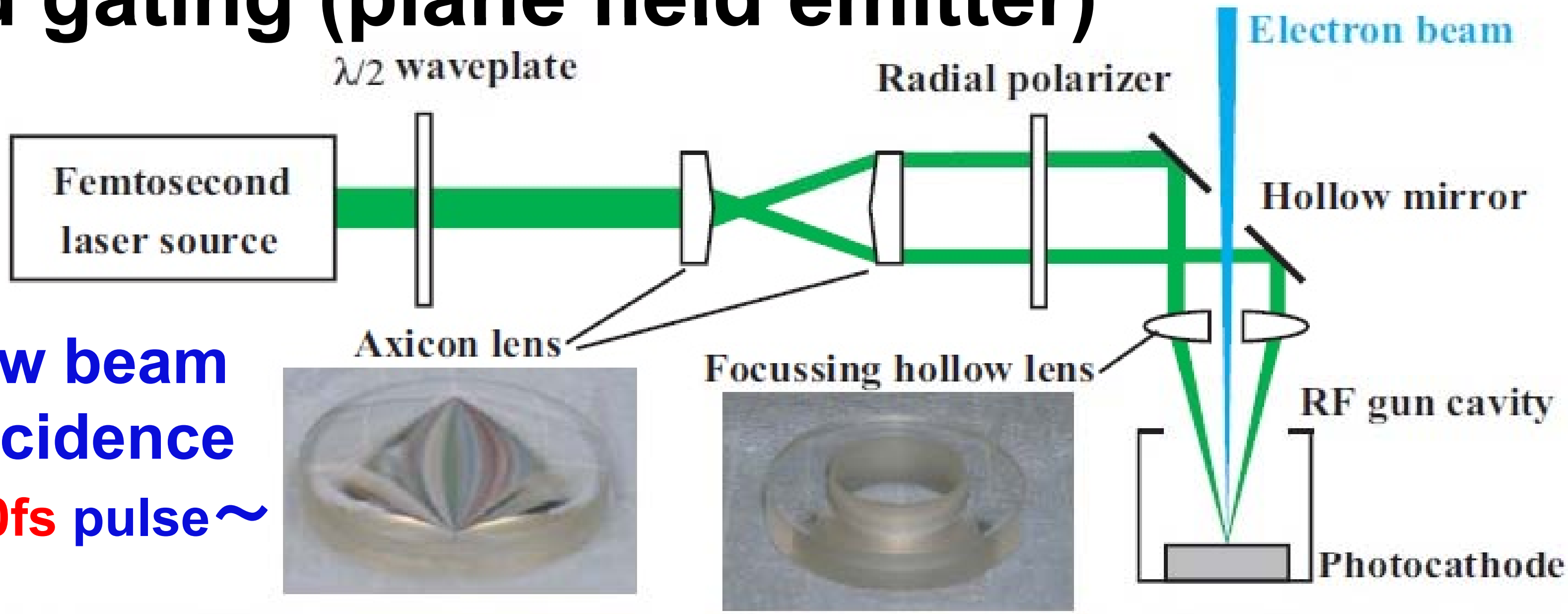
Luiten, "How to realize uniform 3-dimensional ellipsoidal electron bunches", Phys. Rev. Letters 93, 094802 (2004)

Laser: 100 fs with parabolic transverse distribution with 1 mm radius

Cornell DC gun with 500 kV, peak 5MV/m
Bazarov, PRST-AB 8, 034202(2005)



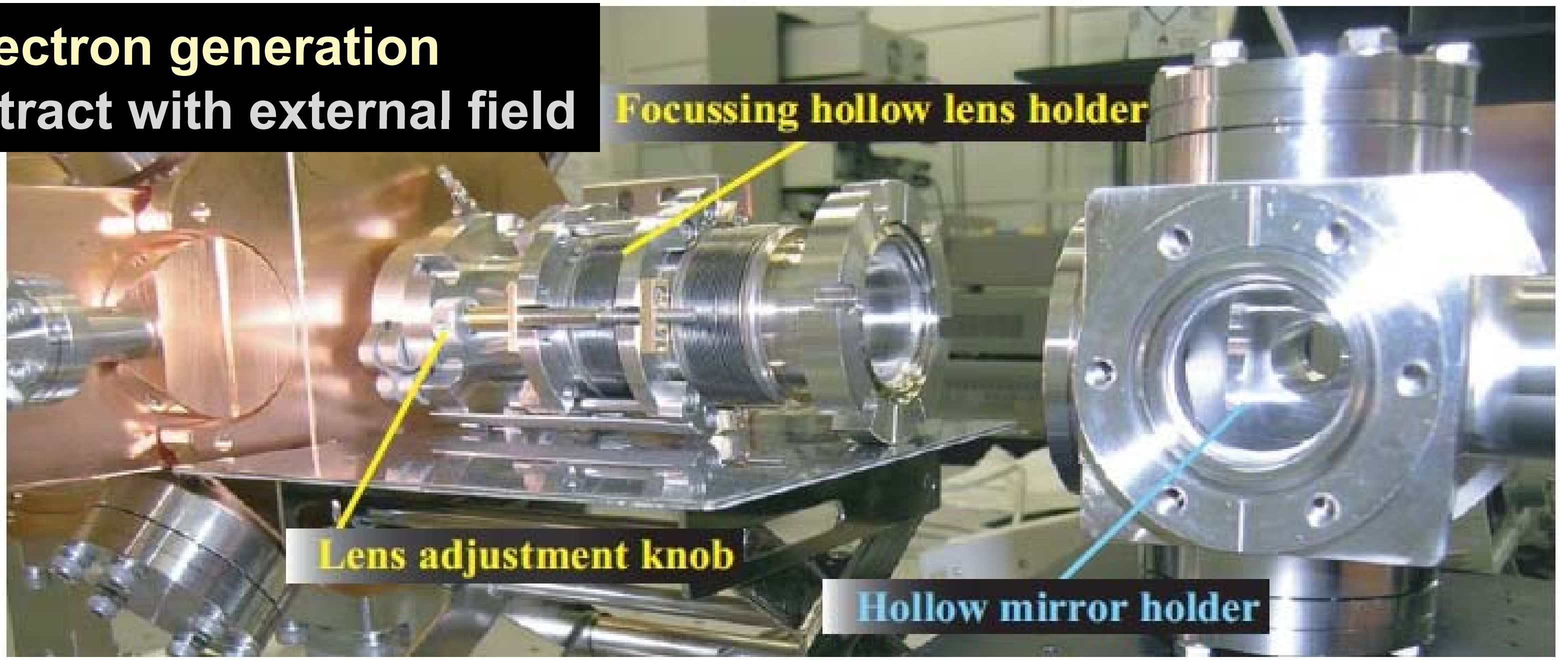
Z-polarization RF gun with laser–induced field gating (plane field emitter)



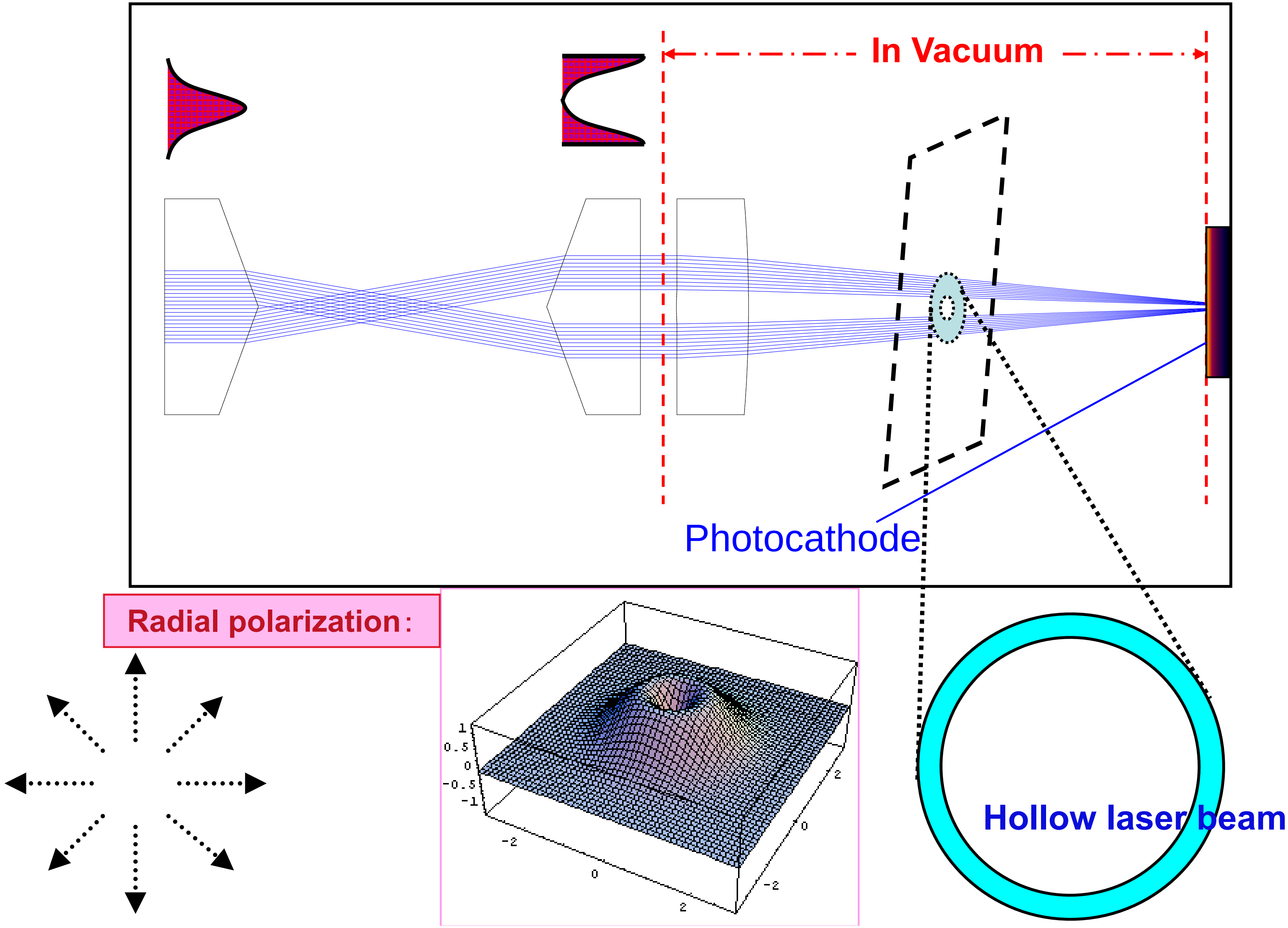
～Hollow beam incidence with 100fs pulse～

Z-pol. : electron generation

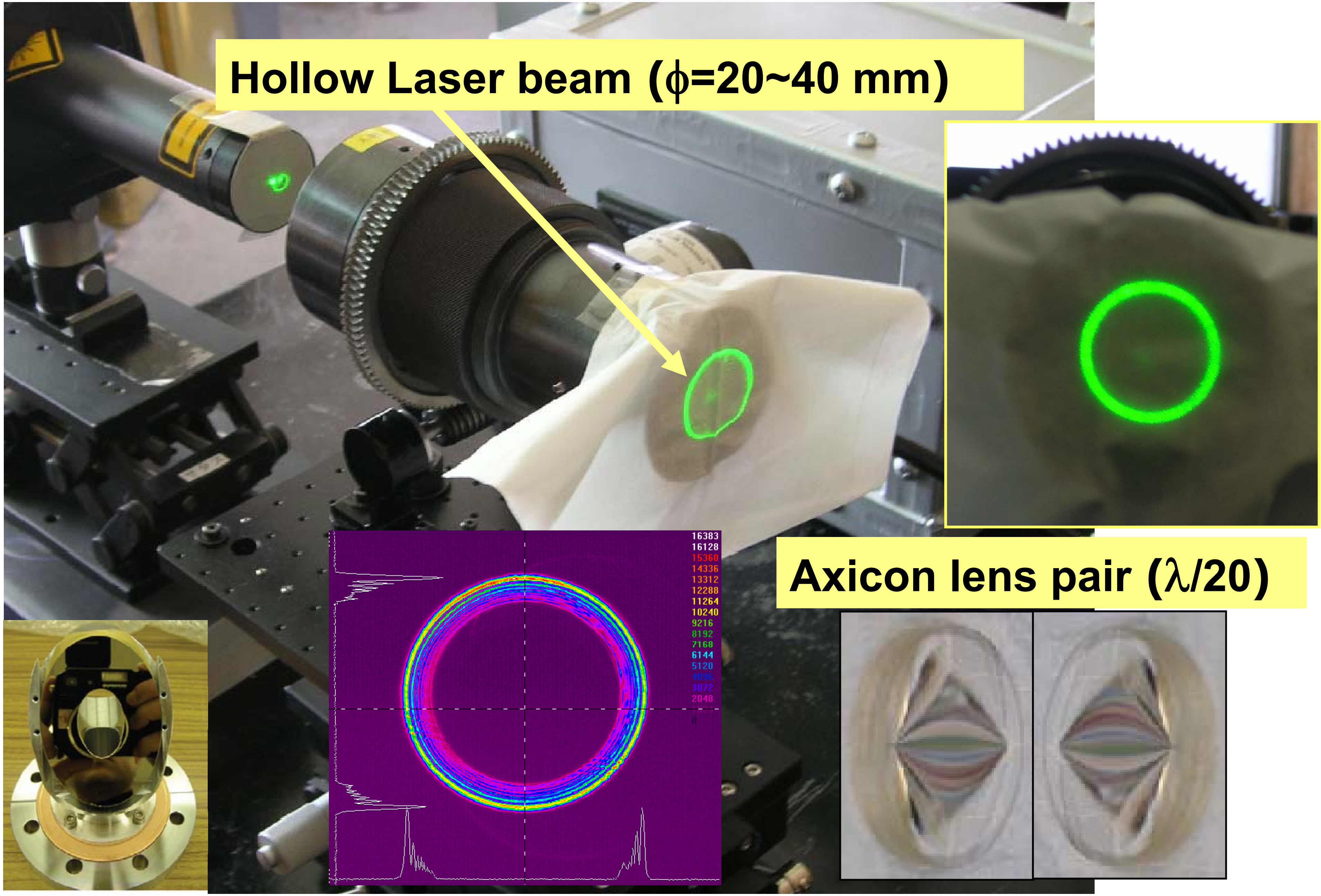
E-gun: extract with external field



Generation of hollow laser beam



Generation of hollow laser beam

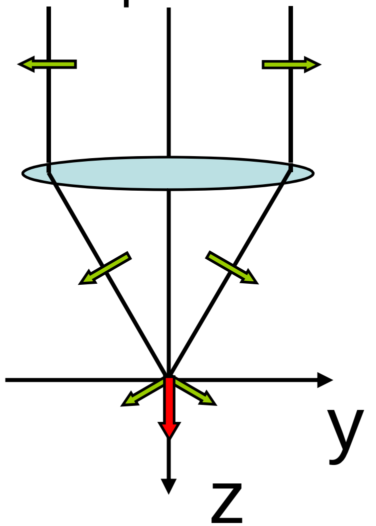


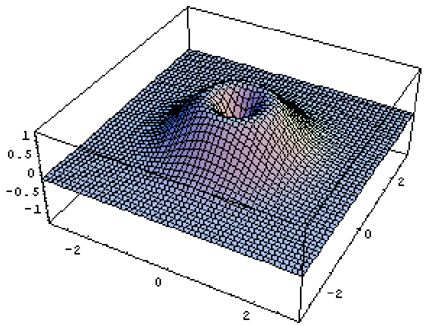
Work function of various metal cathode

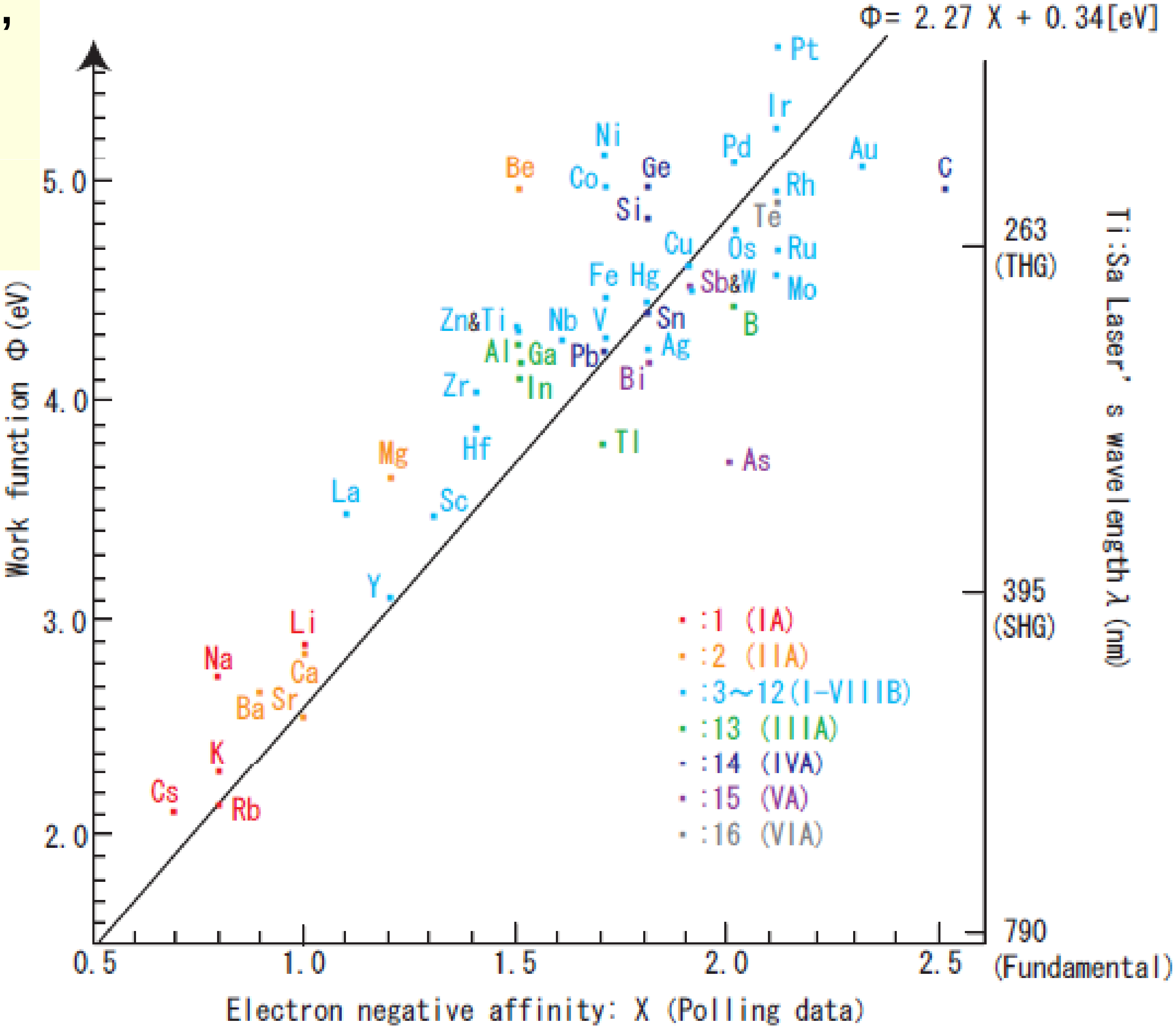
With 1~2GV/m field, Work function reduces ~2eV.

Drive Laser wave-length can be IR.

Radial polarization

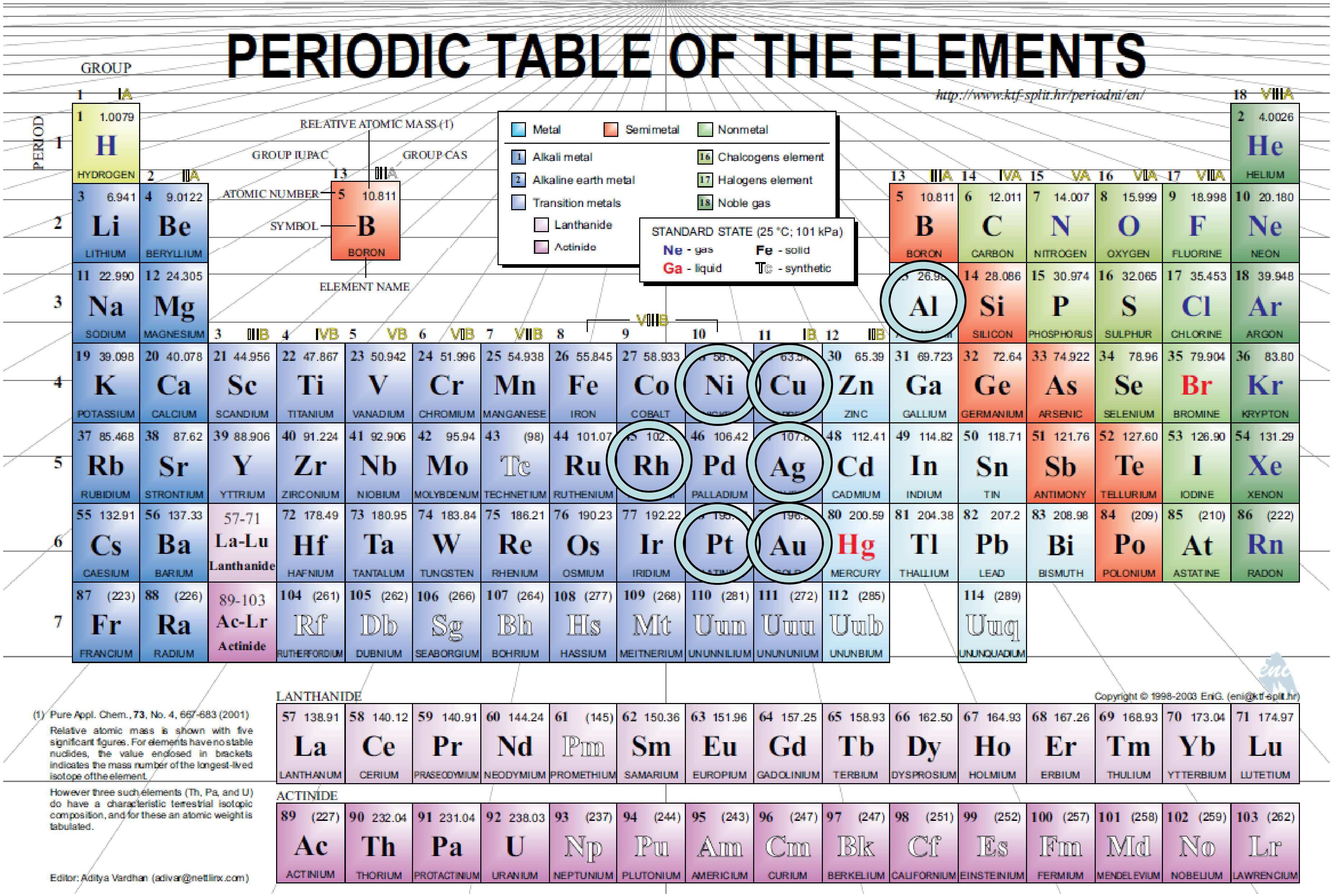




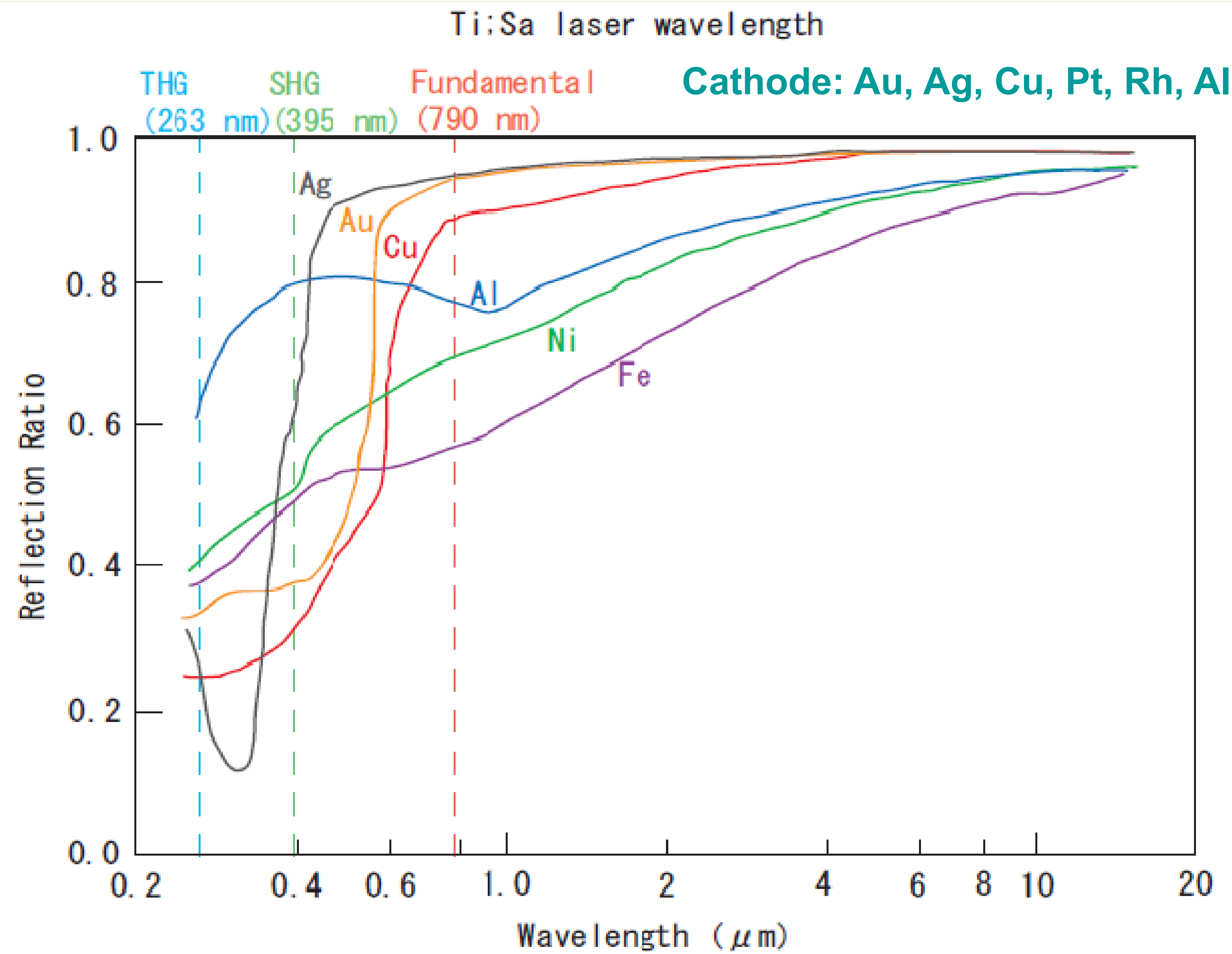


Cathode candidates for UV Z-polarization

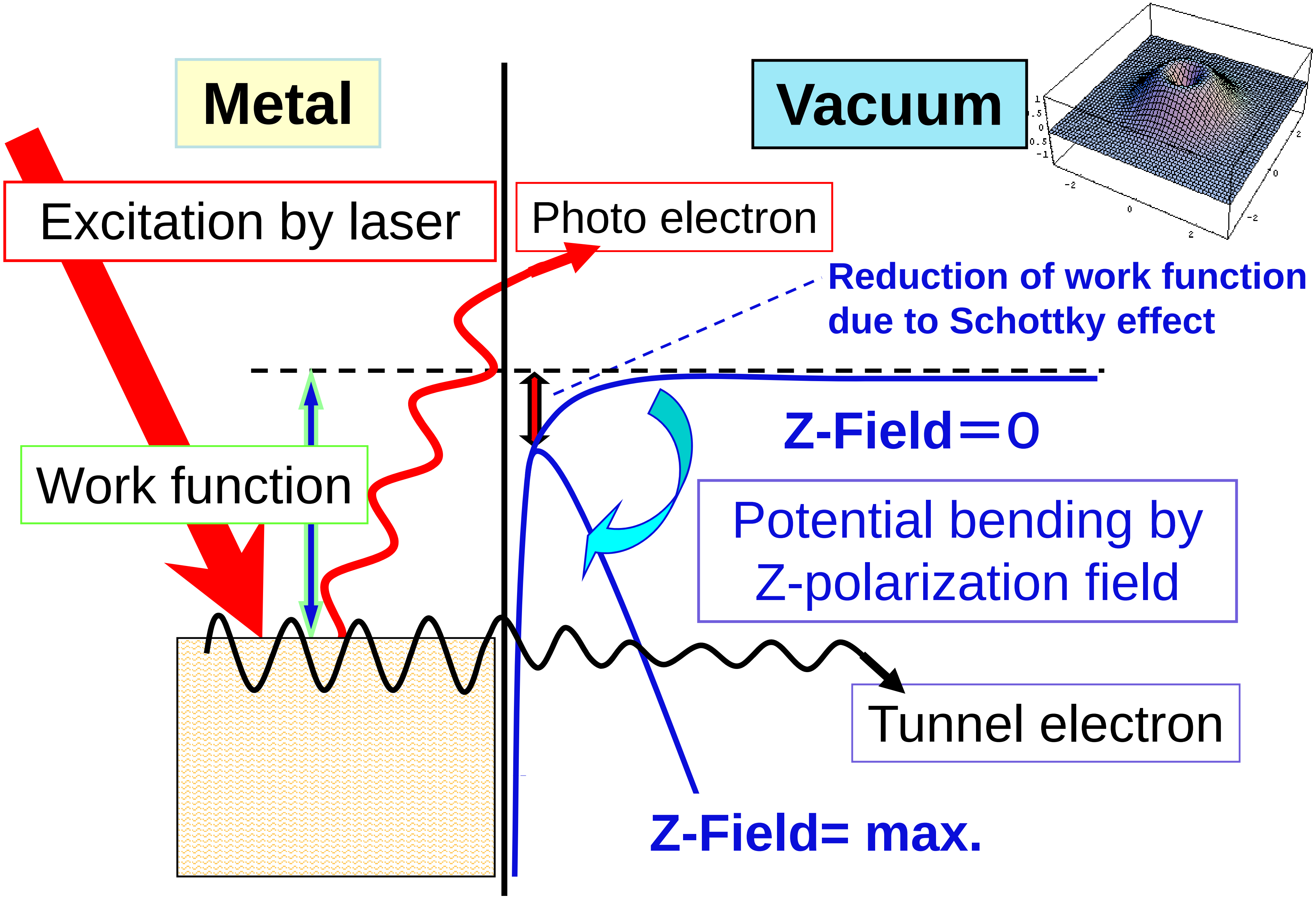
Cathode: Au, Ag, Cu, Pt, Rh, Al, Ni



Reflection ratio of robust cathode candidates

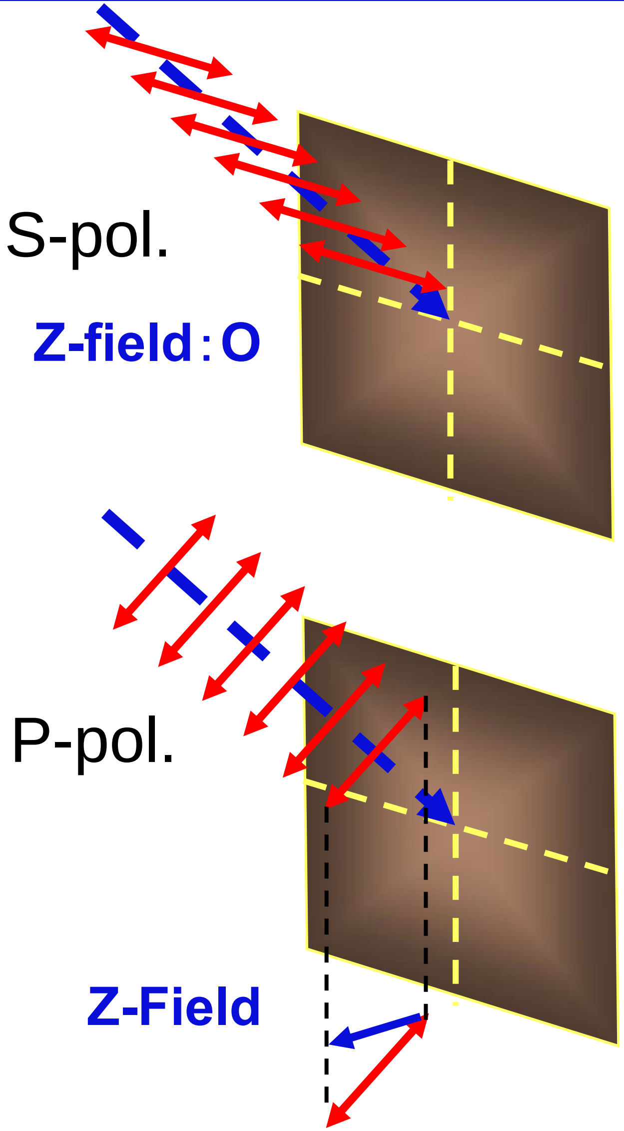


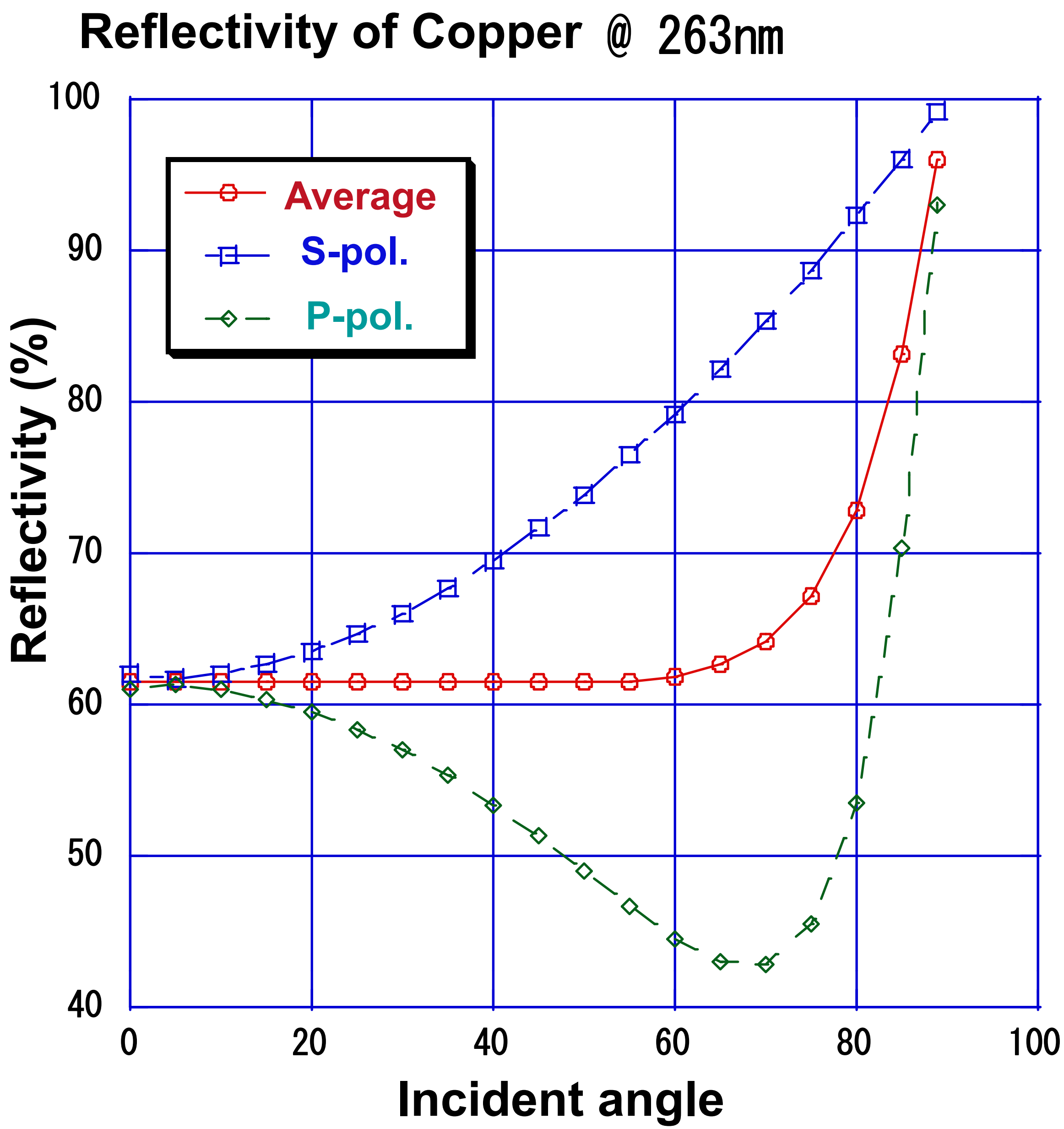
Is the response of metal cathode femtosecond ?



Incident angle dependence of reflectivity (Cu)

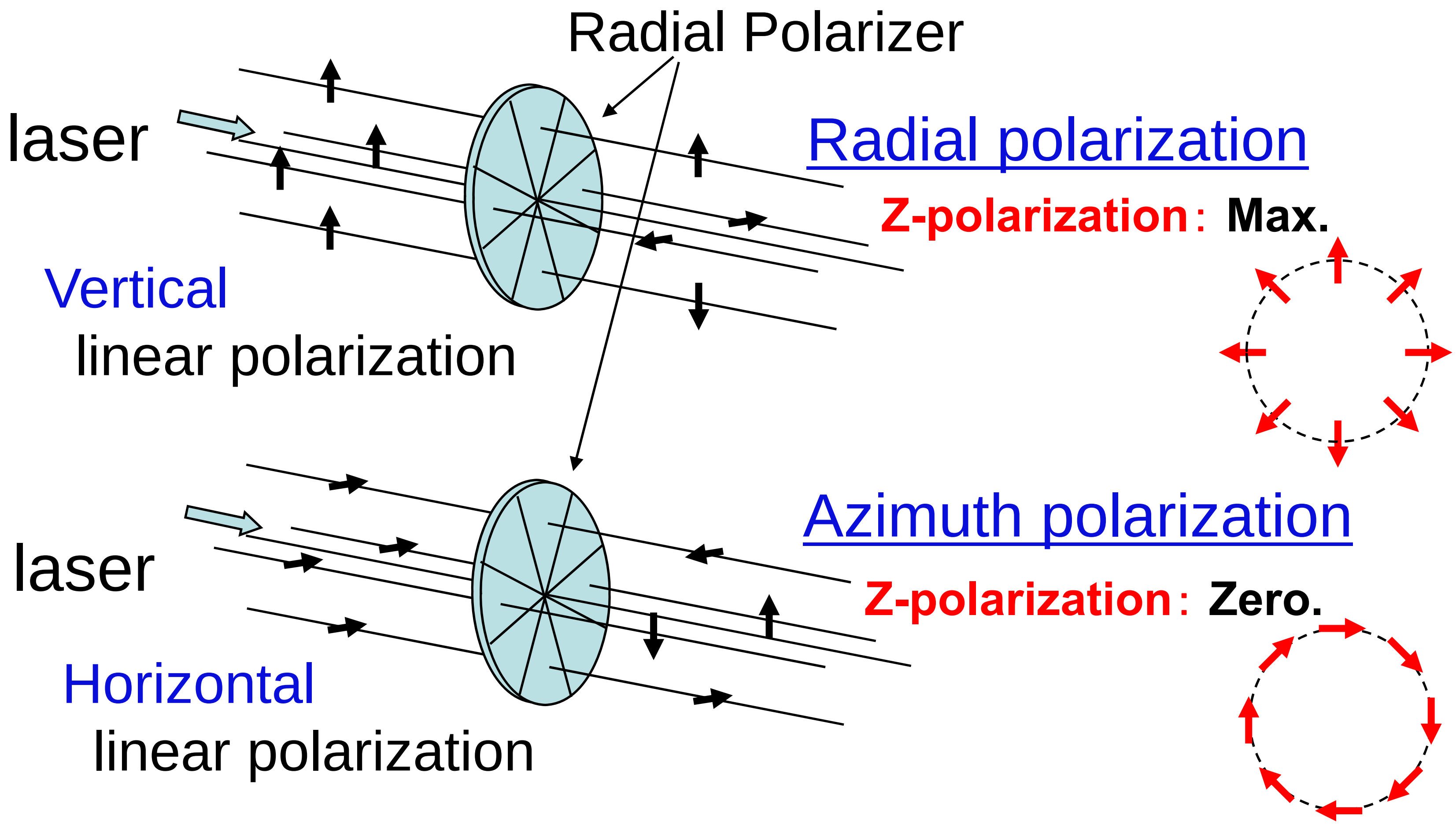
Why oblique incidence higher QE than normal ?





Feasibility test for Z-polarization effect

(Comparison between radial & azimuth polarization)

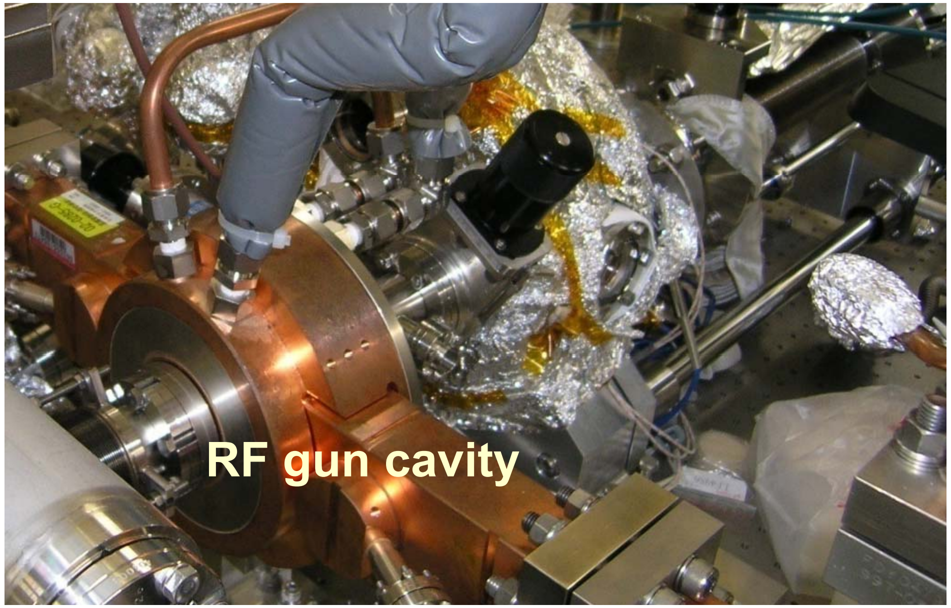


(1) **We can switch radial to azimuth with rotating half waveplate!**
(2) **Comparison between radial and azimuth polarization can tell Z-polarization effect on the cathode (spot size & photon density).**

Experiment setup for different cathode test

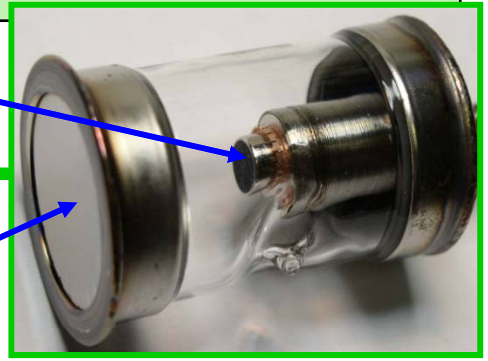
Cathode: Au, Ag, Cu, Pt, Rh, Al, Ni

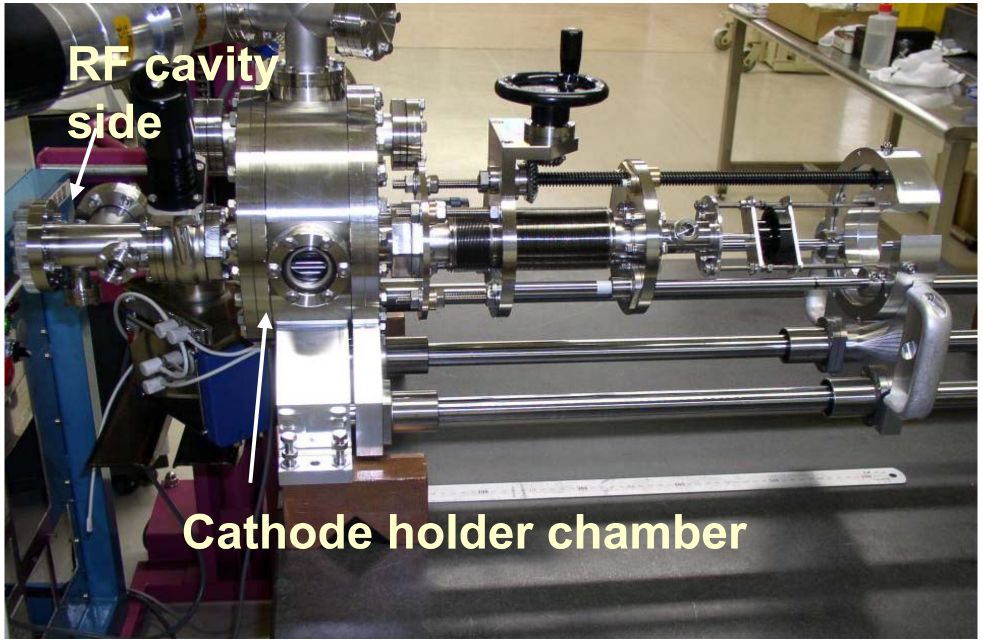
Cartridge type cathode holder accommodates up to 12 cartridges

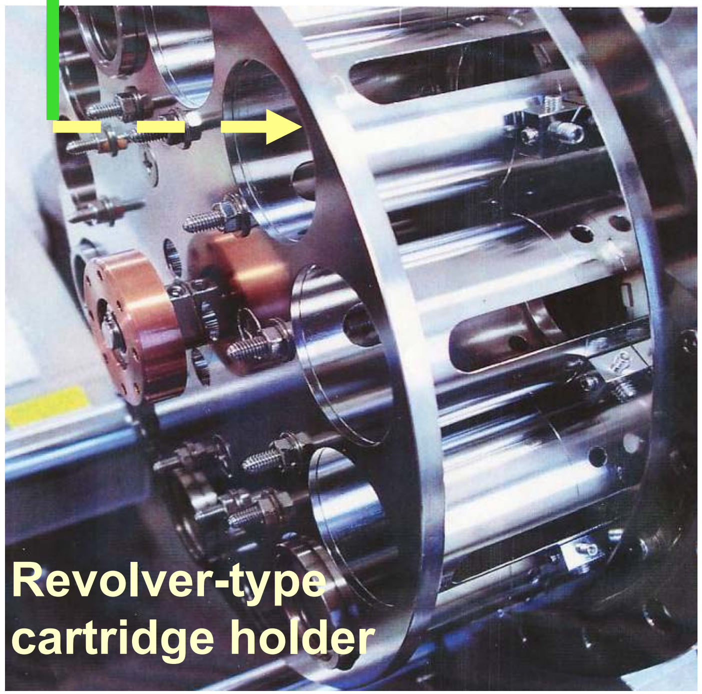


Cathode plug

Kovar Foil

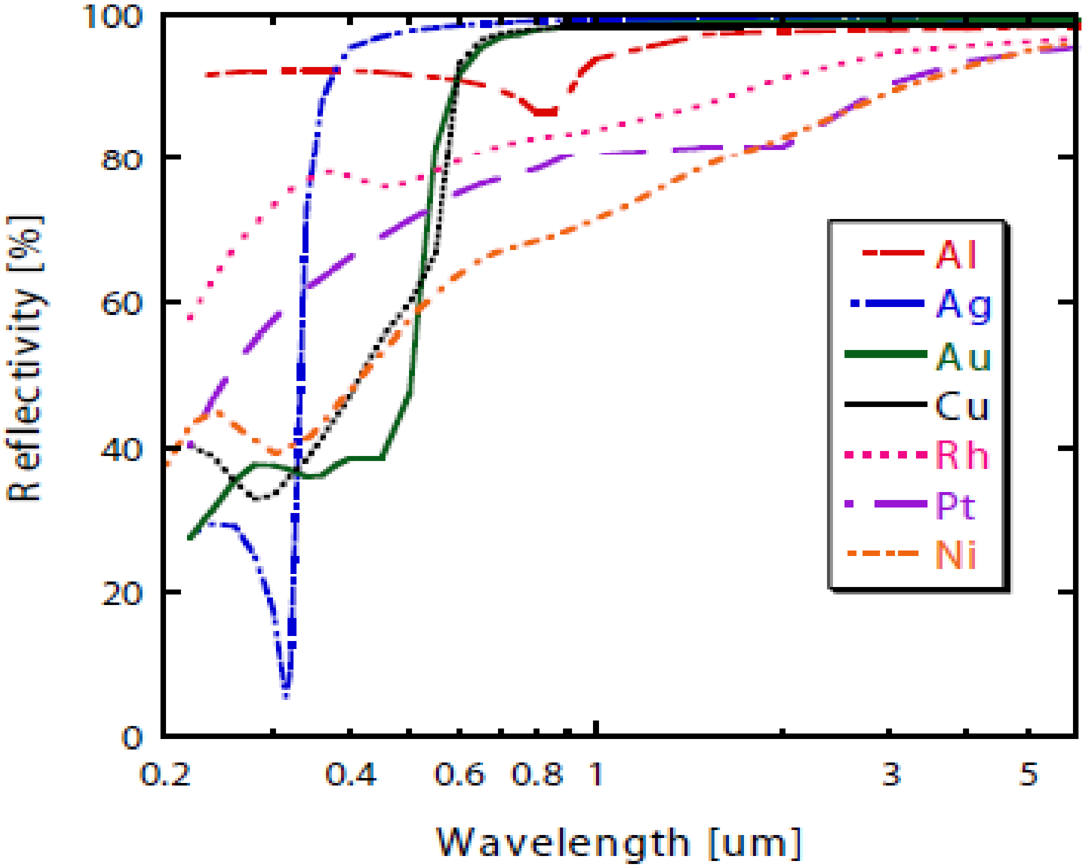






Metal cathode candidates in cartridge tubes

Cathode: Au, Ag, Cu, Pt, Rh, Al, Ni



The question is how fast electron move coherently with laser wake Z-field.

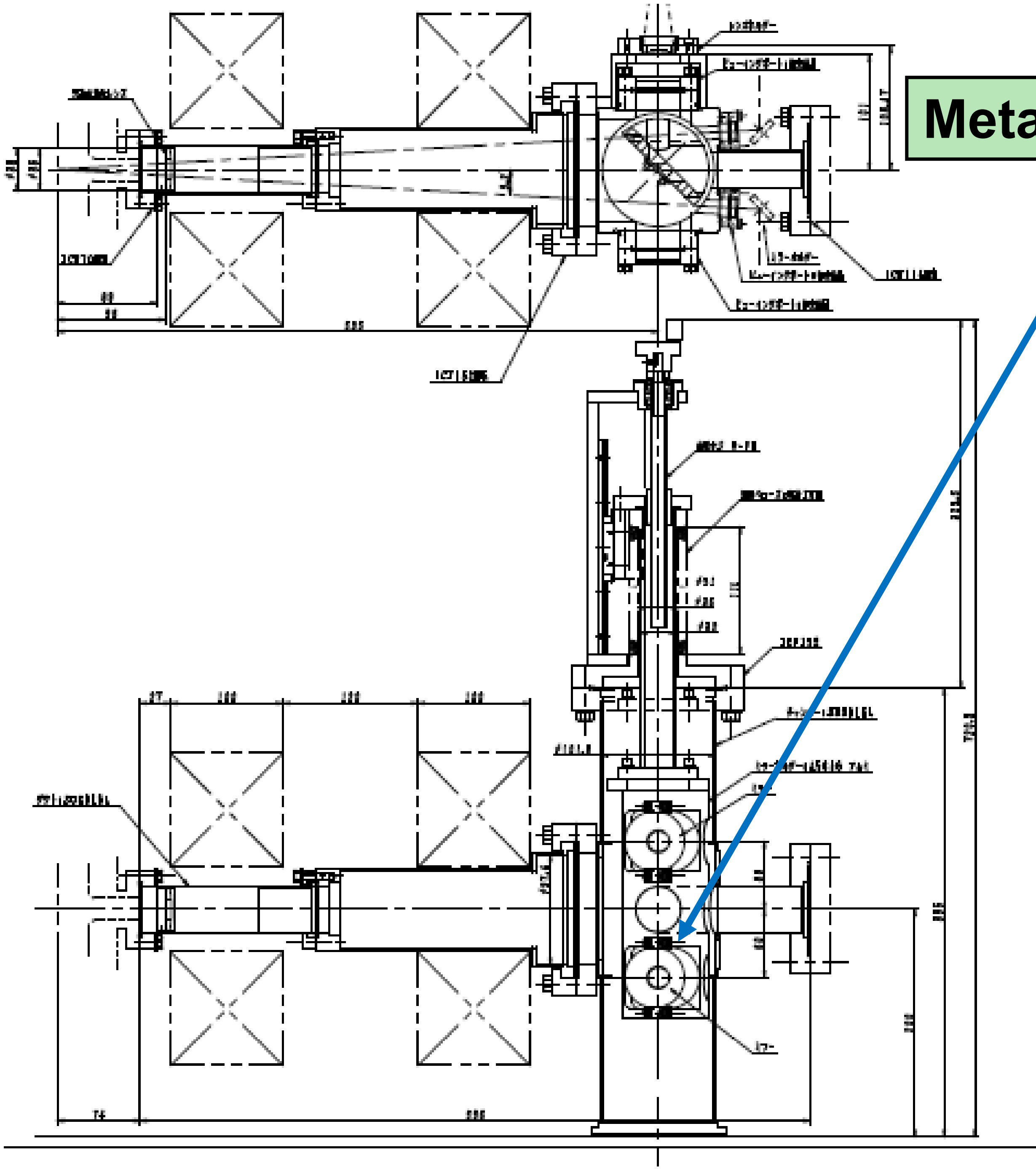
Uncertainty Principle:

$$h/2\pi \sim \text{[fs] [eV]}$$

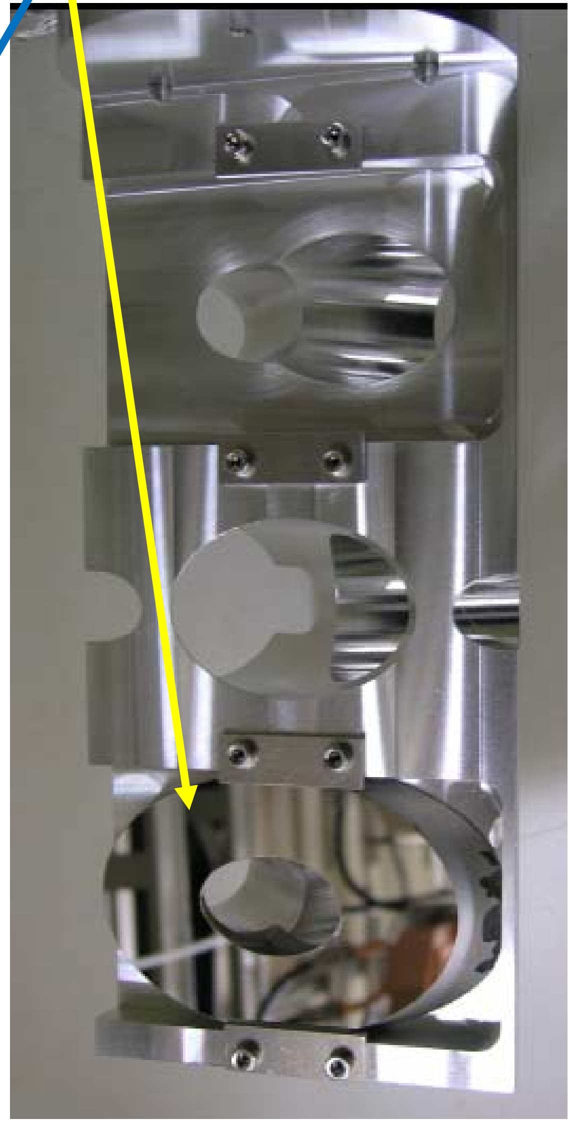
(Dirac's constant)

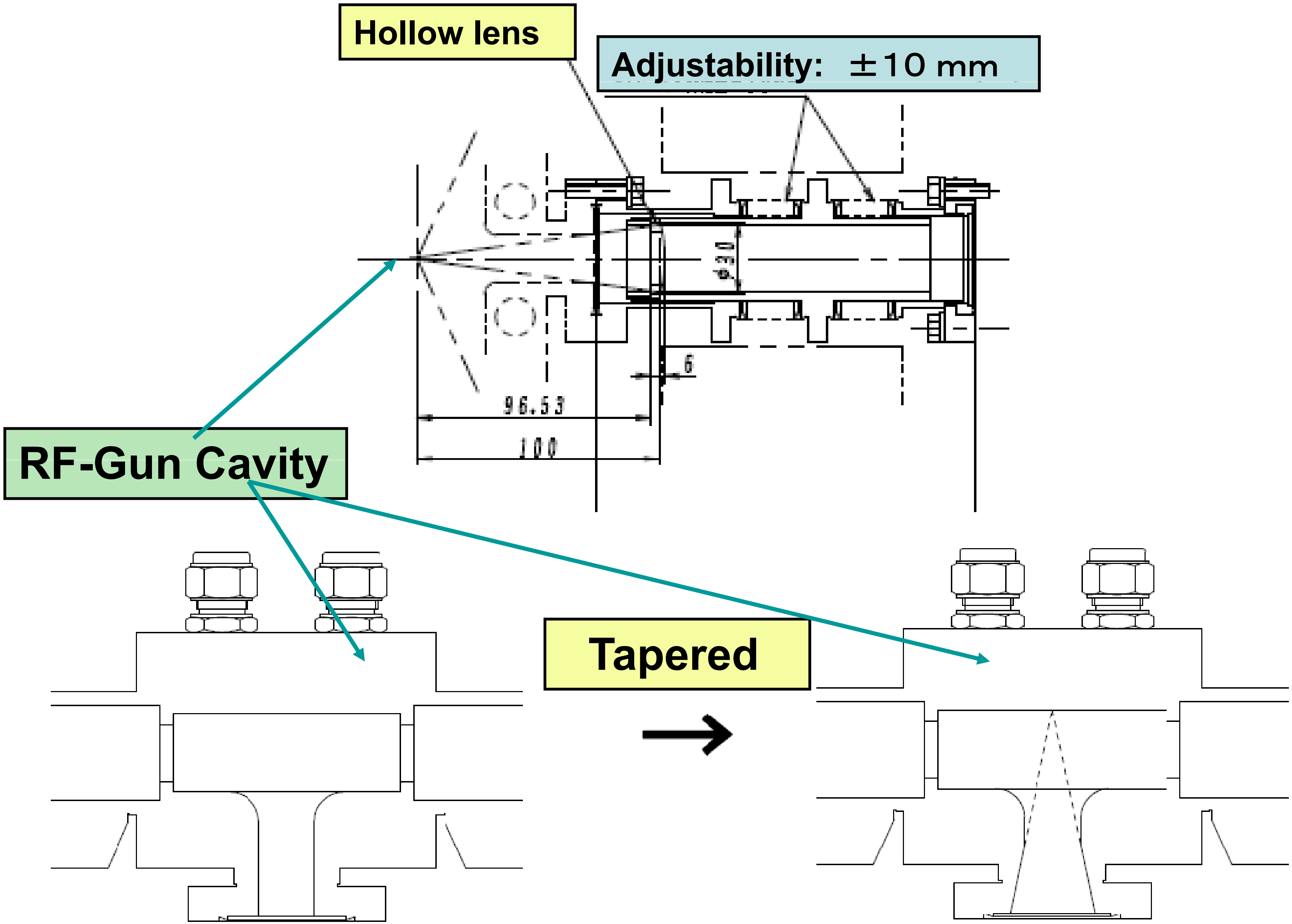
Skin depth:

Metal $\sim \lambda/20$

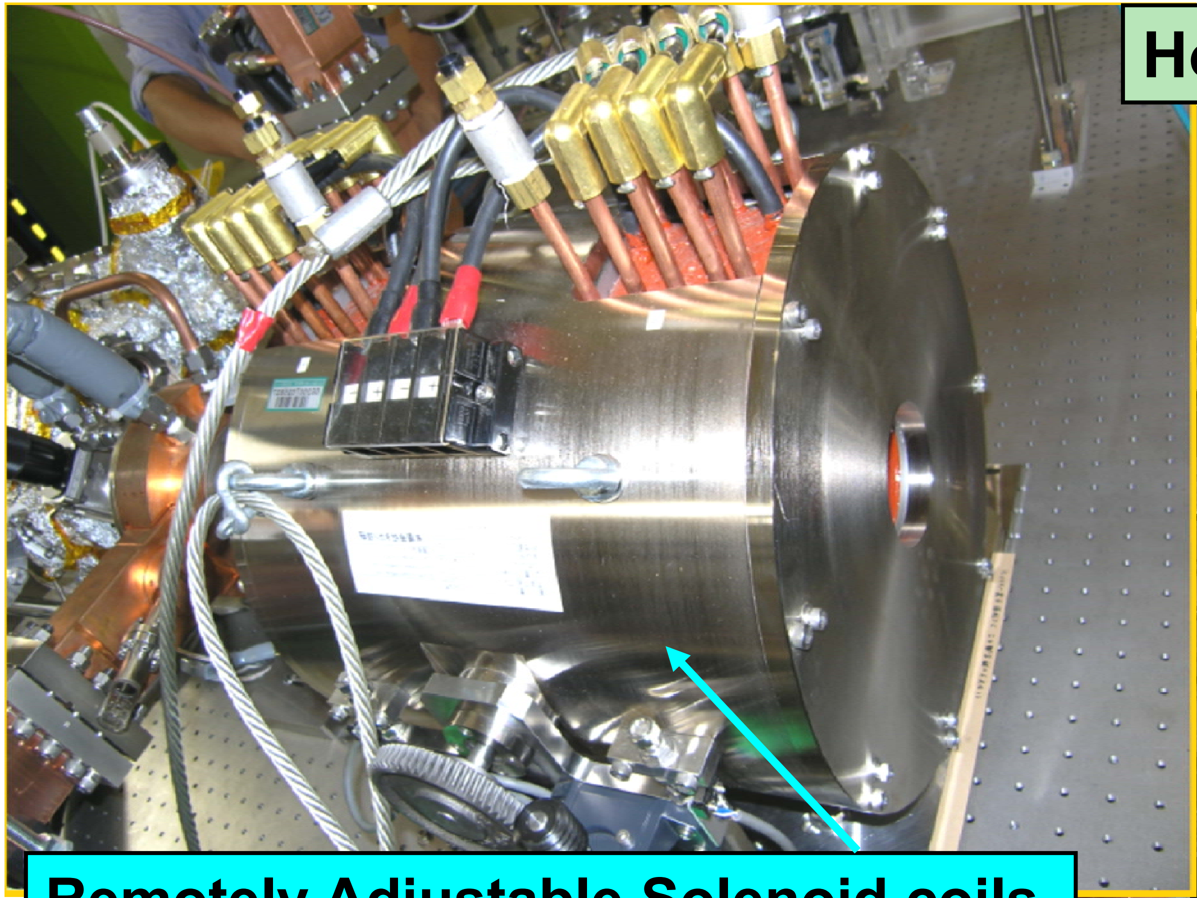


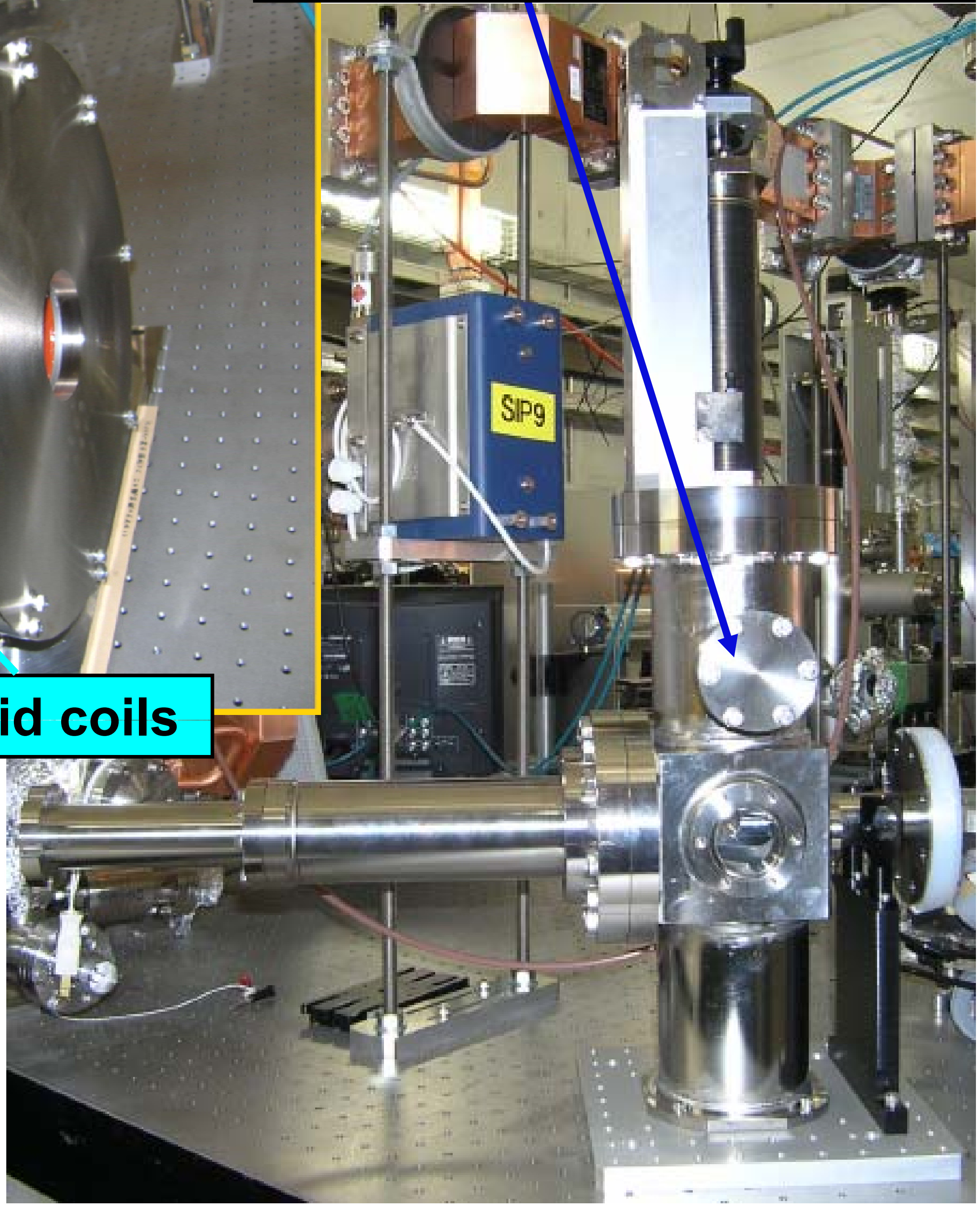
Metal mirrors (Aluminum)




Hollow lens
Adjustability: ±10 mm
φ30
6
96.53
100
RF-Gun Cavity
Tapered

Hollow Mirrors Chamber

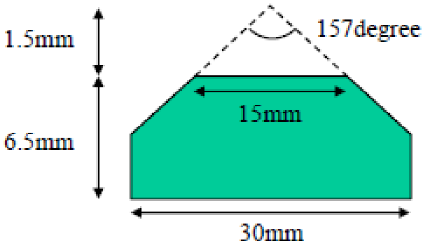


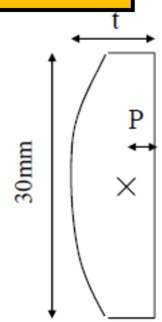


Remotely Adjustable Solenoid coils

2 type of focusing lens:

Axicon lens & convex lens

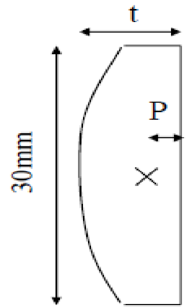




Type1: Convex focusing lens:

~< 10~100μm spot size

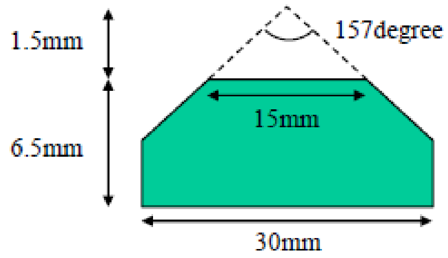
for very low bunch charge generation



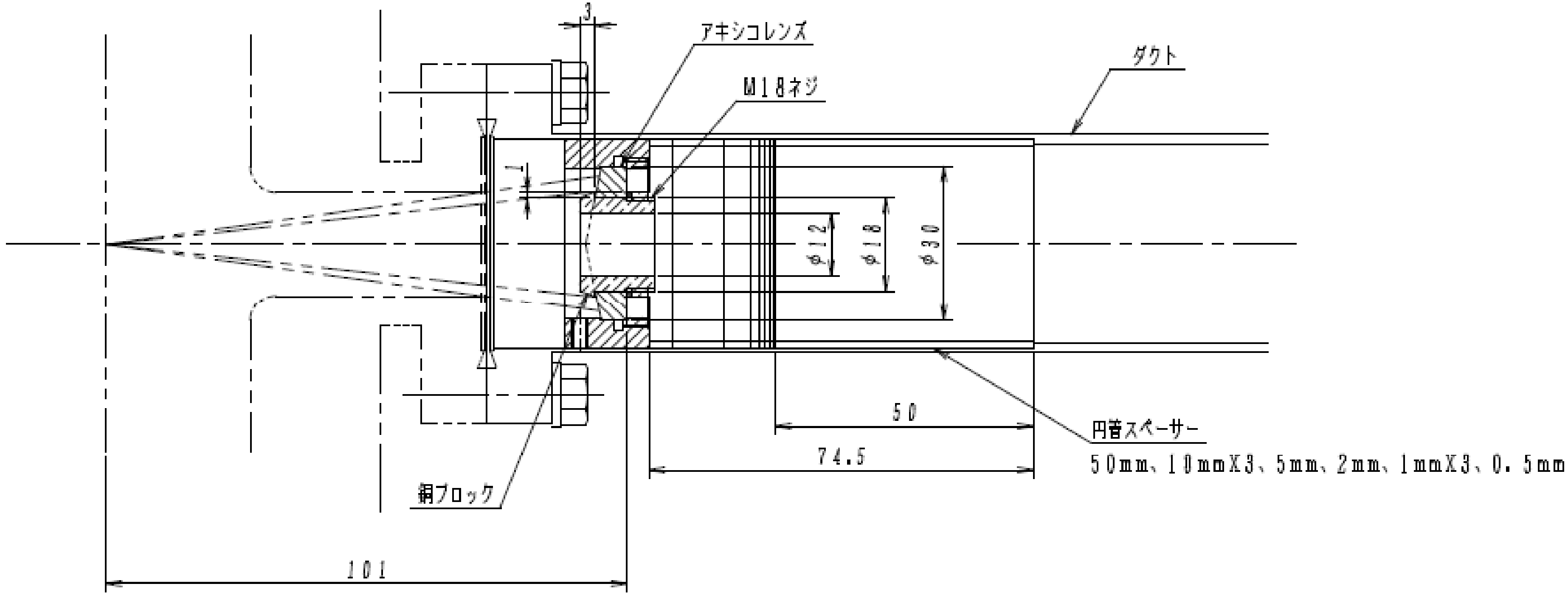
Type2: Axicon focusing lens:

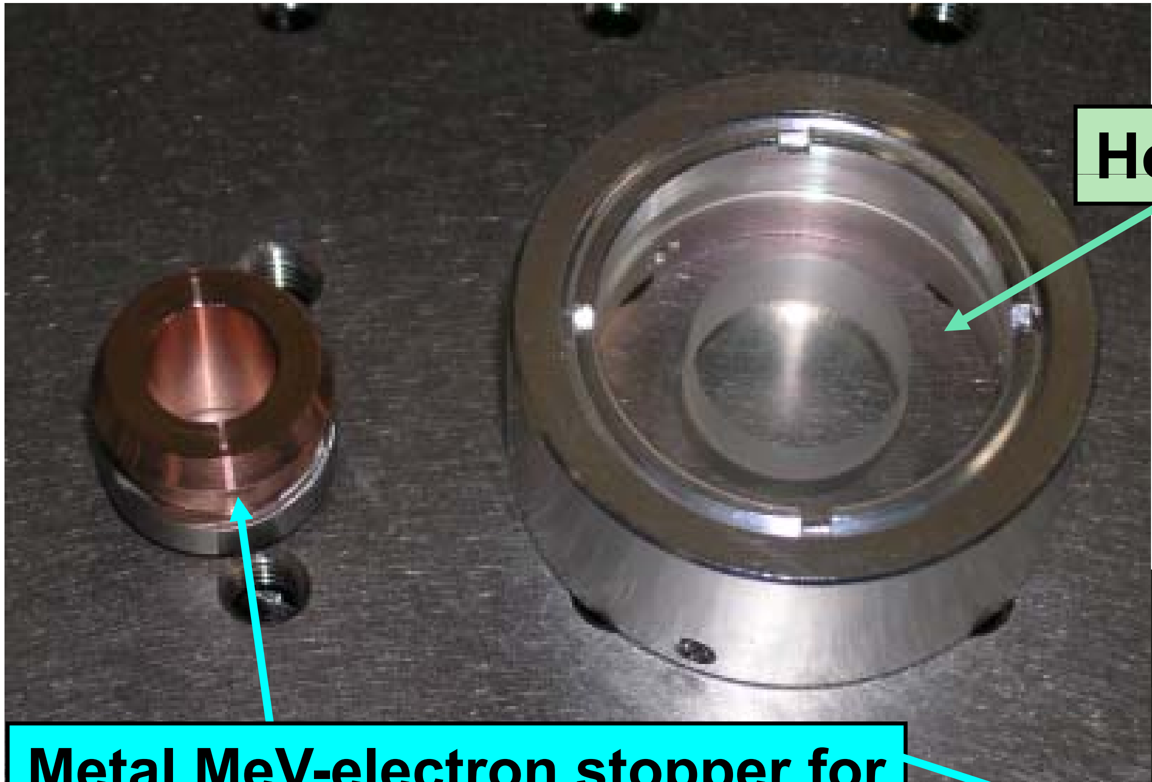
~< mm spot size

for higher bunch charge generation



5mm-copper cover to stop 3MeV electron for lens protection

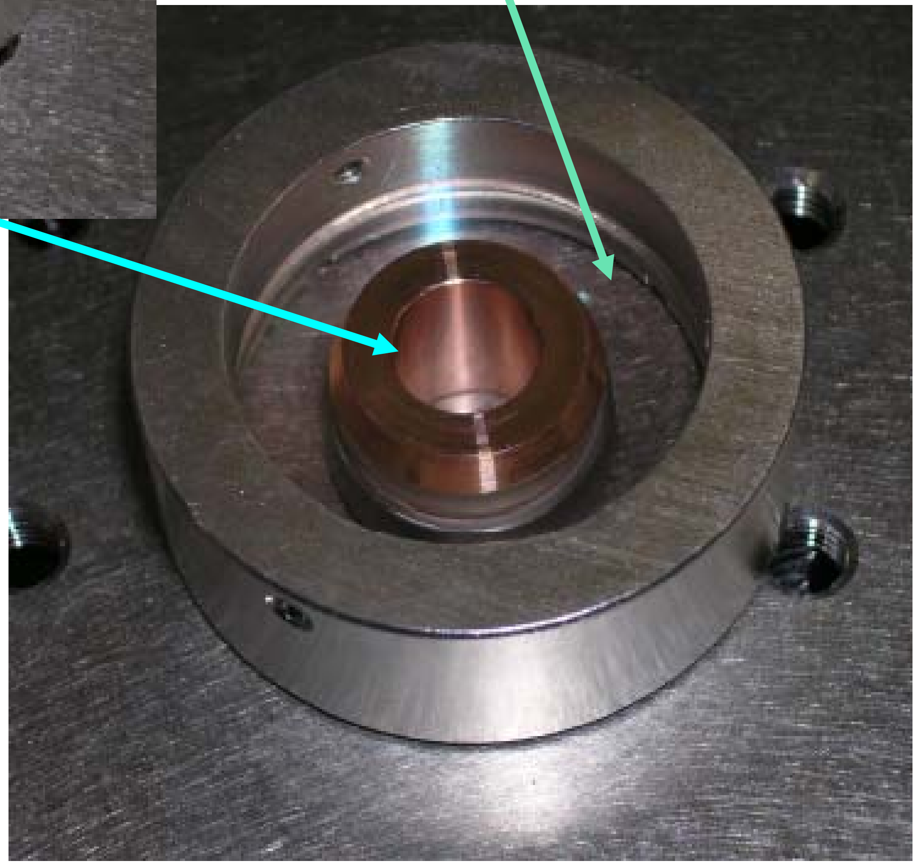




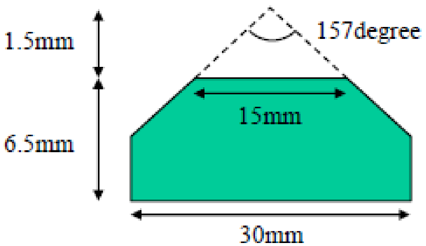
Hollow Lens

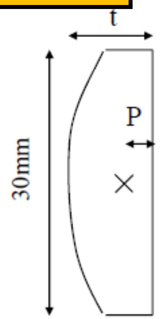
⇒ **Charge-up issue is also considered in this metal cover for the wall of glass lens hole.**

Metal MeV-electron stopper for Lens protection



2 type of focusing lens:
Axicon lens & convex lens

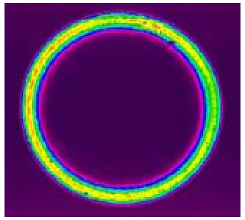


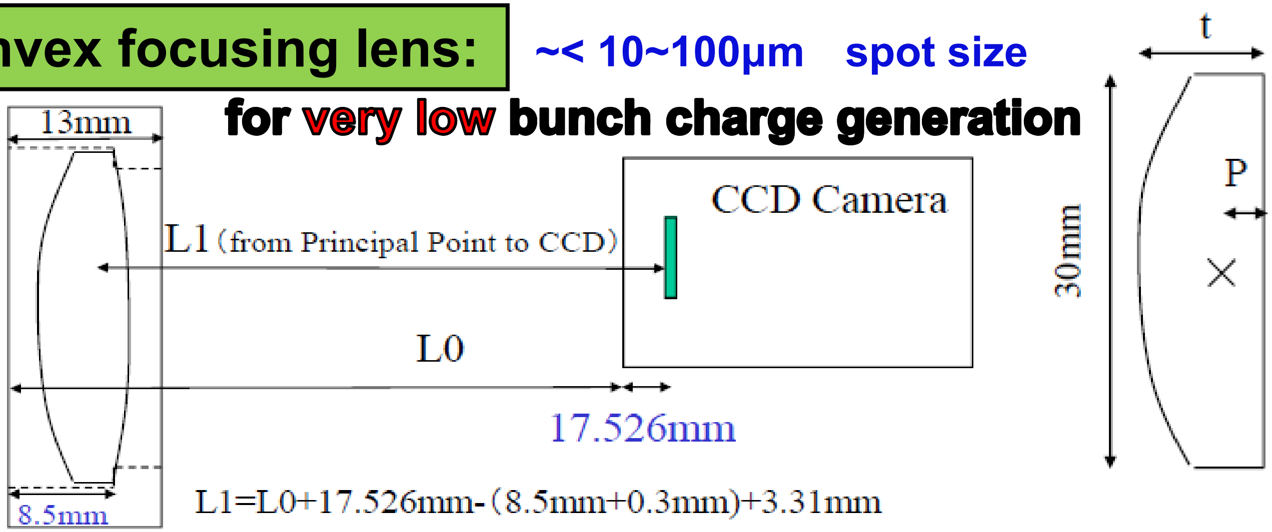


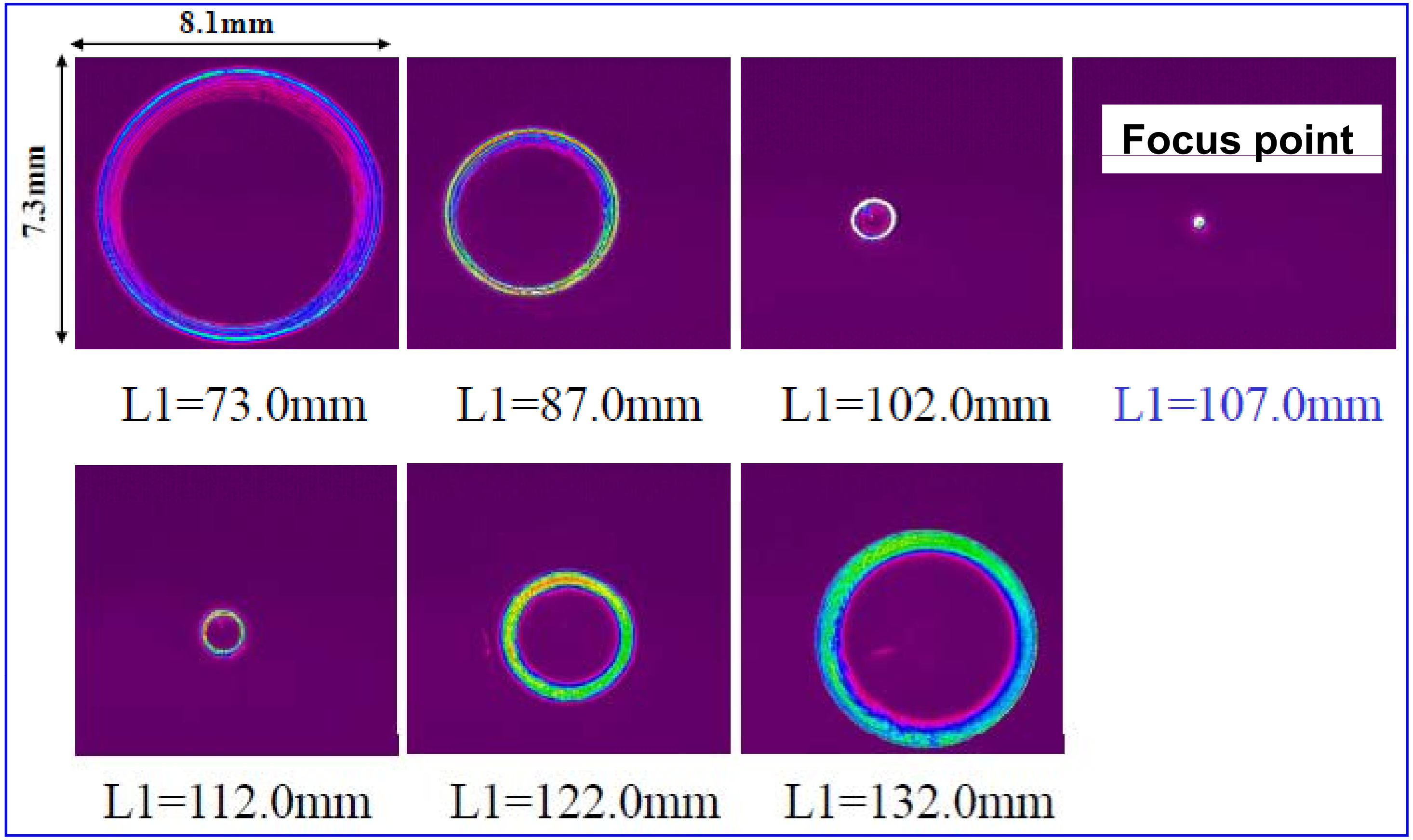
Type1: Convex focusing lens:

~< 10~100μm spot size

for very low bunch charge generation

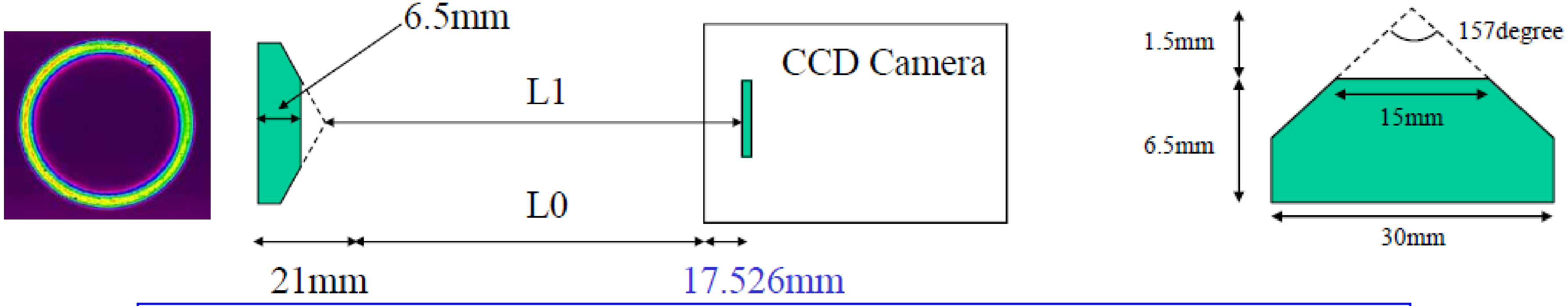


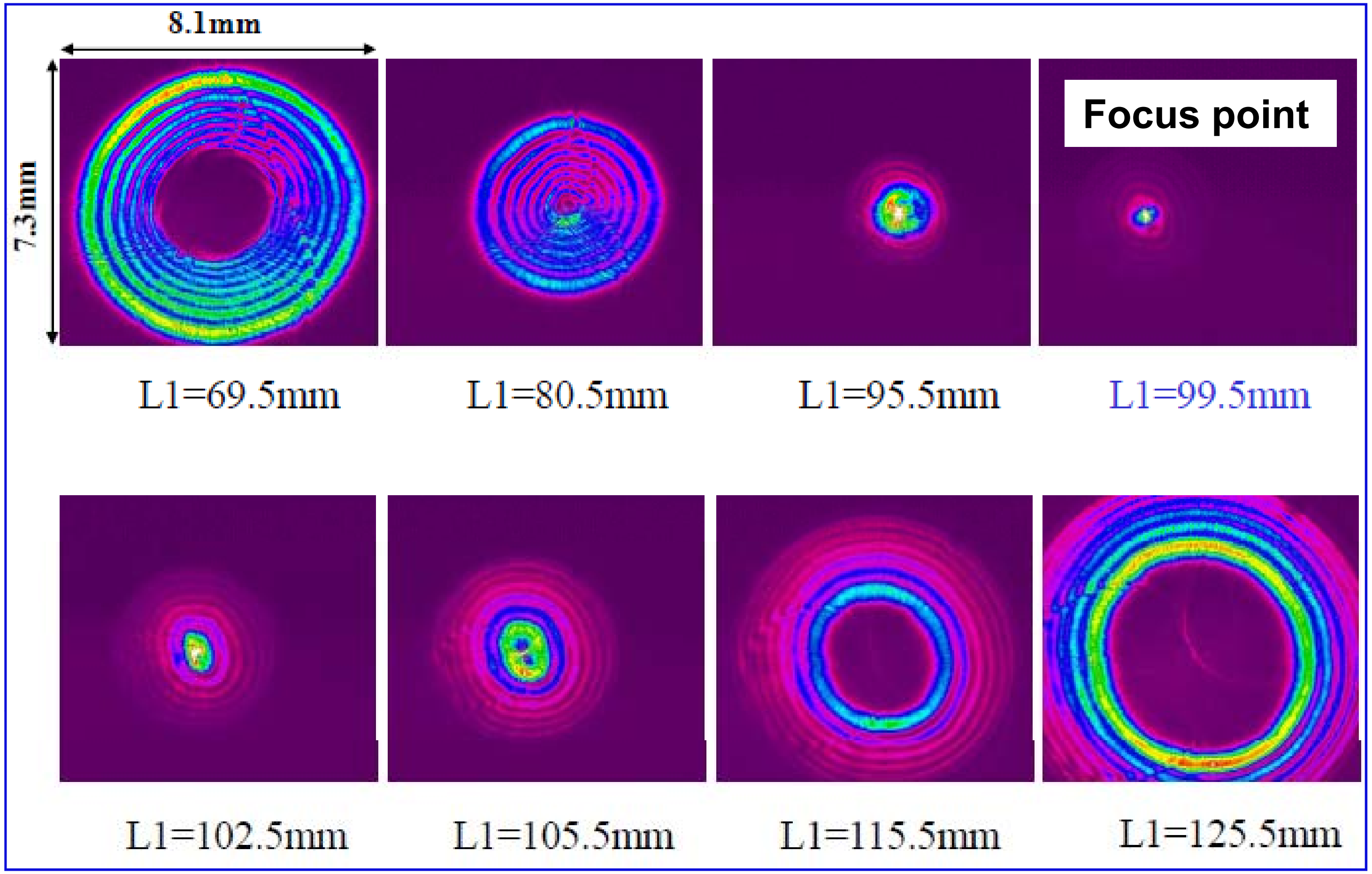




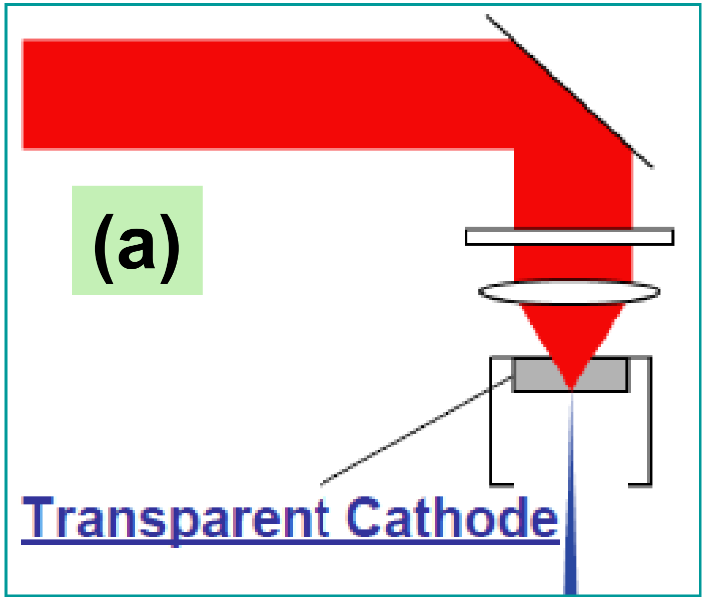
Type2: Axicon focusing lens: ~< mm spot size

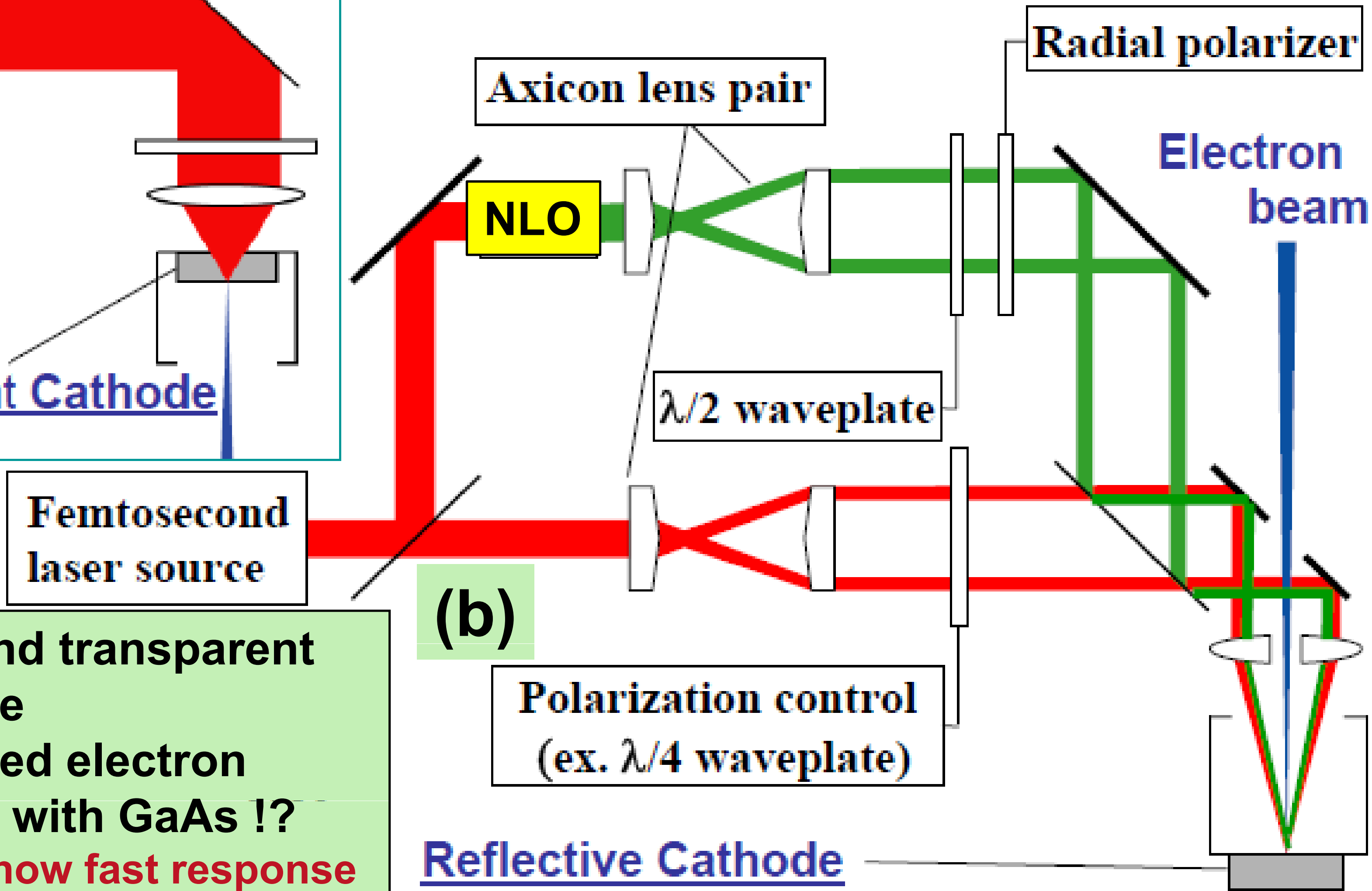
for higher bunch charge generation





Variation of Z-polarization RF gun with laser –induced field gating (plane field emitter)

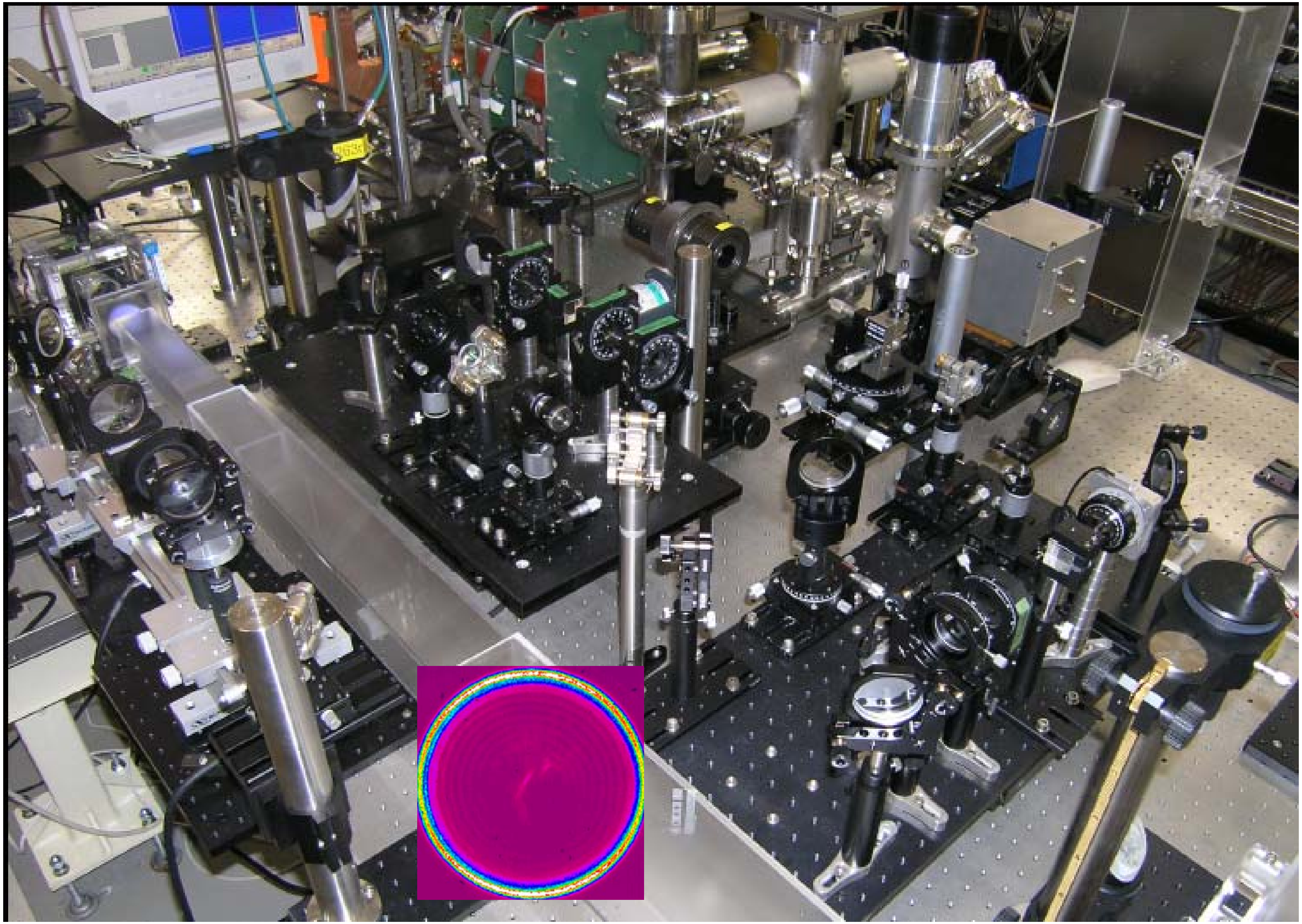




- (a) Diamond transparent cathode
- (b) Polarized electron source with GaAs !?

Question is how fast response of photo cathode!

Z-polarization Gun System at SPring-8

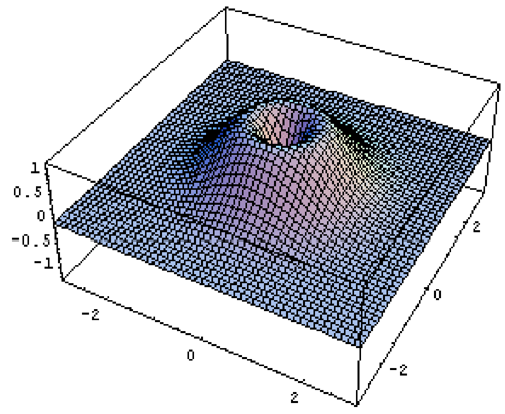


Summary of laser manipulation in 3D-shape & polarization

- Shaping with computer-aided deformable mirror could generate Flattop. It is very flexible to optimize the spatial profile with genetic algorithm. Combining with pulse stacker, 3D- laser pulse shaper was completed.

- The generated Z-polarization can exceed an electrical field of 1 GV/m easily with fundamental wavelength from femtosecond laser oscillator (with long cavity). In the case of NA=0.15, the Z-field of 1GV/m needs **1.2 MW** at peak power for **fundamental (790 nm)** and **0.31 MW** for **SHG**. In the field of 1~2GV/m, the work function of Cu cathode reduces ~2 eV.

- This concept of laser-induced Schottky emission can be applied for photo-cathode DC gun (even for polarized electron source!?).



History & future plan of Z-polarization gun

2006 1. **Z-polarization gun & Hollow beam incidence method were proposed.**

2007 ~2008 2. **Radial Polarizer, Axicon lens pair & their Optical coatings were developed & tested. Feasibility test of Hollow incidence**

Preparing Optics

Feasibility study

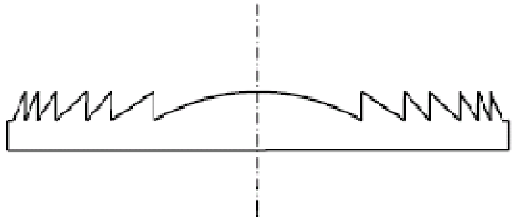
2009 3. **Electron emission with Z-polarization. & selection of ideal cathode material.**

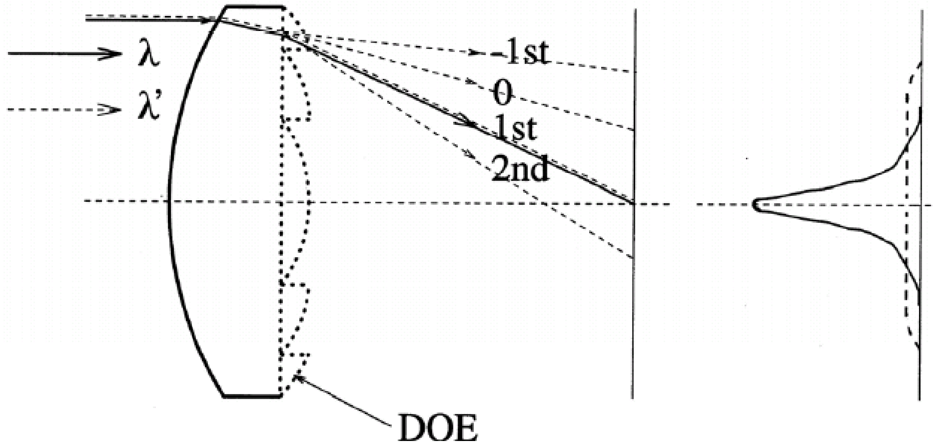
2010 ~2011 4. **Feasibility test of Polarized e-beam generation; Cathode study with T. Nishitani**

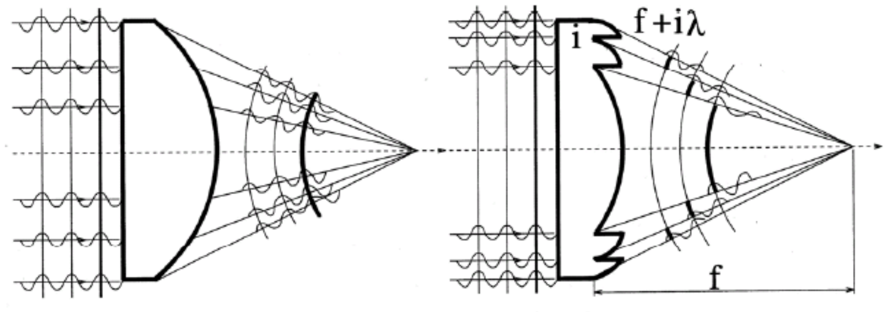
A. Next shaping optics?

A1. Holographic optics can 3D-shape in UV !?

DOE & HOE can be a goal of Laser shaping. However, we have to fix the structure of optics through studying optimal pulse shape with adaptive optics!!



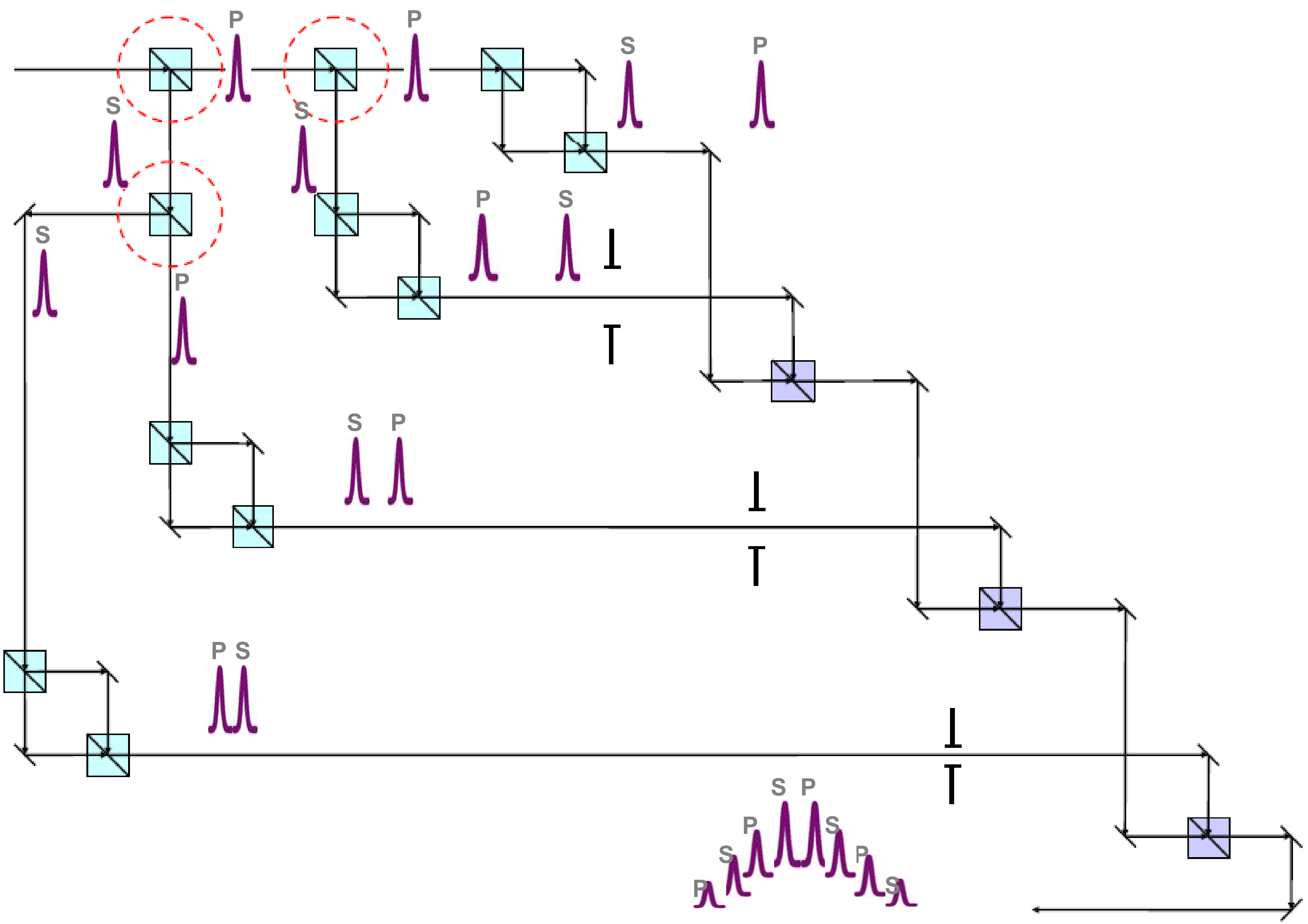




(a) conventional lens (b) kinoform

Chromatic aberration is stronger than conventional optics. But, this characteristics can be used for temporal pulse shaping!?

A2. 4-arm Pulse Stacker for quasi-ellipsoidal shaping?



A3. Hollow incidence with a hollow fiber bundle

Fiber bundle beam shaper for reflective photocathode